THE UNIVERSITY OF ALBERTA

RELEASE FORM

NAME OF AUTHOR IAN HUMPHREYS

TITLE OF THESIS SPEED-ACCURACY TRADE-OFF:FACTORS INFLUENCING THE RELATIONSHIP BETWEEN SPEED AND ACCURACY OF MOVEMENT

DEGREE FOR WHICH THESIS WAS PRESENTED DOCTOR OF PHILOSOPHY

YEAR THIS DEGREE GRANTED FALL, 1987

THE UNIVERSITY OF ALBERTA

SPEED-ACCURACY TRADE-OFF: FACTORS INFLUENCING THE RELATIONSHIP BETWEEN SPEED AND ACCURACY OF MOVEMENT

by

© IAN HUMPHREYS

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF PHYSICAL EDUCATION AND SPORT STUDIES

EDMONTON, ALBERTA

FALL, 1987

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled SPEED-ACCURACY TRADE-OFF:FACTORS INFLUENCING THE RELATIONSHIP BETWEEN SPEED AND ACCURACY OF MOVEMENT submitted by IAN HUMPHREYS in partial fulfilment of the requirements for the degree of DOCTOR OF PHILOSOPHY.

DEDICATION

I would like to dedicate this thesis to my parents. Their love and support of all of my activities has been enormous. I would also like to dedicate it to my wife, Corinne, who saved me from self destructing.

ABSTRACT

The results of five experiments which examined the relationship between speed of production and accuracy of aimed movements are presented. In Experiment 1 it was demonstrated that movements to a target could be speeded without loss of accuracy. Using a modified Fitts (1954) tapping task, in which targets of unequal size were paired together, it was demonstrated that movements to a given target could be speeded and become more accurate if the size of the paired target was increased. It was hypothesised that subjects partition available resources for target acquisition between the targets in a target pair. Increasing the width of one target reduced the demand associated with that target and allowed subjects to devote more resources to the acquisition of the more demanding target. Experiment 2 replicated the findings of the first experiment using a greater range of amplitudes of movement. In Experiment 2 strategies of visual fixation employed by subjects when performing the reciprocal tapping task were observed by filming the subject's eyes when they were performing the task. Frame by frame analysis revealed that as the size of one target in a pair increased relative to its partner that the frequency of alternating fixations between targets was reduced, the mean time of fixation on the larger target decreased while that on the small target increased, and the total time of fixation on the large target decreased while that on the small target increased. It was proposed that the pattern of eye fixations observed reflected a deliberate strategy on the part of subjects. The relationship between availability of visual feedback information and the production of aimed movements was discussed. Experiment 3 compared and contrasted methods of constraining movement commonly employed in experiments examining the phenomenon of speed-accuracy trade-off. It was demonstrated that movements constrained by target width could be performed faster but with equal accuracy to movements constrained by movement time. Similarly, movements constrained by movement time were performed faster but with equal accuracy to movements paced by a metronome. It was proposed that such task manipulations place differing demands on the subject. The importance of understanding task composition and its relation to speed and

accuracy of movement was discussed. Experiment 4 demonstrated that not all task manipulations designed to bring about an increase in task demand are perceived as such by subjects. In a reciprocal tapping task, subjects were presented with target pairs ranging in width from 8 mm to 32 mm. Twenty five target pairs, increasing in 1 mm steps from 8 mm were presented in random order to the subjects. Analysis of movement time and error data revealed that subjects produced movements in five distinct movement times. This categorization corresponded with the subjects subjective evaluation that only five distinct target widths had been presented. The results of this experiment were discussed in relation to the ability of subjects to make categorical judgements. Workload margin, that increase in task demand required to bring about a change in output, was estimated to be in the order of 0.4 bits. Experiment 5 further demonstrated that performance is partly based on subjective perception of task difficulty. In a reciprocal tapping task, target pairs were presented to subjects in a variety of contextual surrounds. In two conditions the contextual surround created a perceptual illusion in which one target appeared smaller than its partner, even though both targets were the same diameter. In such conditions subjects produced output which was consistent with the targets actually being of different widths. The results of the five experiments suggest that performance outcome is based on the interaction of a number of factors. These factors include resource allocation policies, perceived and actual task demands and mechanical response factors. It is proposed that a more complete understanding of the interrelation of such factors is essential if a clear understanding of the relationship between speed and accuracy of aimed movements is to be gained.

ACKNOWLEDGEMENT

I would like to acknowledge the terrific support that I have been fortunate to receive from my supervisor and friend, Dr. Bob (Willy) Wilberg. In the years I have been at the University of Alberta, Bob has been a constant source of encouragement and support as well as a font of information. I will never forget the ideas that were generated in Bob's company while we were having "just one". Thanks a lot Bob.

I would also like to acknowledge the advice and suggestions given to me by my committee members. I feel privileged to have had them serve on my committe.

I would also like to acknowledge the support given to me by my wife, Corinne. She has had to put up with a lot in the time it has taken me to complete this work.

Table of Contents

LIST OF FIGURES

Figure		Page

LIST OF ABREVIATIONS

1. A: Amplitude
2. W: target width
3. W(e): Effective target width
4. MT: Movement Time
5. ID: Index of Difficulty
6. Ip: Index of Performance

1. INTRODUCTION

The increase in error associated with attempts to speed aimed movements, referred to as speed-accuracy trade-off, has been the focus of much theoretical and empirical work in the psychological domain. Since the pioneering work of Fullerton and Cattell (1892) and Woodworth (1899) numerous researchers have presented theories attempting to account for the apparent trade-off between speed and accuracy of movement (Crossman and Goodeve, 1983; Fitts, 1954; Howarth, Beggs and Bowden, 1971; Meyer, Smith and Wright, 1982: Schmidt, Zelaznik and Frank, 1978; Schmidt, Zelaznik, Hawkins, Frank and Quinn, 1979). Such theories fall into two general categories. For slow aiming movements (> 250 msec) error is thought to be associated with the time available for the processing of feedback information and the issuance of within movement corrections. As movement time decreases, less time is available for the processing of feedback information, with the result that errors cannot be corrected (Crossman and Goodeve, 1983; Howarth, Beggs and Bowden, 1971). For rapid movements (< 250 msec), which cannot rely on feedback mediated corrections, errors are thought to be related to the variability associated with some programmed parameter of movement such as the magnitude and duration of accelerative impulse (Schmidt et al. 1978, 1979; Meyer, Smith and Wright, 1982)

For slow aiming movements, Fitts' Law (Fitts, 1954) remains one of the few precise laws describing the production of aimed movements. Fitts attempted to account for the trade-off between speed and accuracy of movement by using a 'universal constant', the Index of Difficulty (ID), which quantified the information content of aimed movements. ID was defined in information terms as $\log_2 2A/W$ where A represented the amplitude of the movement and W the width of the aimed for target. Fitts demonstrated that movement time in a reciprocal aiming task was a linear function of the Index of Difficulty such that $MT = a + b \log_2 2A/W$. Fitts' Law has accommodated data from a number of experimental sources (Knight and Dagnall, 1967; Fitts and Peterson, 1964; Fitts and Radford, 1966) and while many attempts have been made to improve upon Fitts' equation, none has resulted in any

significant change (Welford, 1960; Keele, 1981; Meyer, Smith and Wright, 1982).

It is generally accepted that the three factors; information rate, tapping speed and accuracy, and processing resources are connected. The commonly observed connection is that as information rate increases so does the demand on resources. Knowles (1963) presented a conceptual model of human performance which viewed the operator as the controller of a pool of resources of limited capacity. Increasing task difficulty increased demands on these limited resources resulting in decreased performance. Moray (1967) and Taylor, Lindsay and Forbes (1967) refined the resource theory, arguing that resources could be shared between processing channels and stages of processing rather than being dedicated to a single process or channel at any given time. Theoretical treatments by Kahneman (1973), Norman and Bobrow (1975) and Navon and Gopher (1979) have developed the resource metaphor into a quantitative theory with testable predictions of the effect of workload manipulation on task performance. The resource relationship, although not explicitly stated, is implied in Fitts' Law (1954). Fitts' Law has a number of important implications. First, as the tapping task demands are increased (i.e. move faster; move farther; be more accurate under a given velocity) the information being transmitted by the subject is increased. Second, that as the information rate (demand) is increased, there is a direct and complimentary increase in resource demands. Finally, because of the previous implications, when limitations in performance are perceived or observed they are the result of either resource limitations, or mechanical response limitations such as muscle viscosity, maximum rate coding or strength to weight ratios (Stein, 1982; Mackenzie, 1985). The differences between these two limitations can be made clear through the appropriate experimental procedures and techniques.

The Fitts' (1954) reciprocal tapping task requires that subjects tap alternately between targets of <u>equal</u> width separated by a fixed amplitude. Since information rate is dependent upon the interaction among movement speed, target width, and the distance (amplitude) between targets, variations in one or more of these parameters should cause predictable changes in the amount of information being transmitted. For example, if the width of <u>one</u> of the two targets in the Fitts' tapping task is varied relative to the other, there should be a

predictable change in the rate at which information is handled by the operator (that is, the time required to process and act upon the information required to move towards the larger of the two targets should be less than that required when moving in the opposite direction). Increasing the width of one target in the target pair relative to the other target reduces overall capacity demands on the performer. Since speed and accuracy of movement are dependent upon the difficulty of the movement expressed in information terms (Fitts, 1954), a manipulation which reduces overall demand should result in movements which are faster and/or more accurate. Therefore, if one target in the reciprocal tapping task is made wider relative to its partner <u>then movements to the smaller fixed target should be faster and/or more accurate</u> than they would be if the same small target were paired with an equal width target. Within the current understanding of the phenomenon of speed-accuracy trade-off, as expressed in Fitts' Law, these predictions could not be tolerated, since: a) increased velocity should result in increased error; and b) increased accuracy should result in reduced velocity.

The hypothesis, that the reduction of the overall demand associated with an aiming task results in movements which are faster and/or more accurate, was tested in Experiment 1. Specifically it was hypothesised that a reduction in overall demand brought about by increasing the width of one target in a target pair relative to its partner, which remains fixed in width, should have result in movments to the fixed target which were faster and/or more accurate than the case in which two equal sized targets were paired together.

An increase in the speed of movement, without an associated increase in error, would be a contravention of the speed-accuracy trade-off phenomenon described by Fitts (1954).

2. EXPERIMENT ONE

The foregoing hypotheses were tested using a modified Fitts' tapping task. The modification to the reciprocal tapping task employed by Fitts (1954) involved varying the relative sizes of the two targets in the target pair. Four target widths were selected; 1, 2, 4, and 8 cm. All possible two target combination pairs were formed, giving a total of 16 target pair combinations ranging in difficulty from the 1 cm vs 1 cm pair to the least difficult 8 cm vs 8 cm pair. Since all possible target pair combinations were formed a target would appear as the right hand target in one target pair (i.e 1 cm vs 4 cm) and as the left target in the reverse pair (i.e. 4 cm vs 1 cm). A target consisted of 2 parallel lines 15 cm in length, separated by a distance equivalent to the target width. The dependent variables of interest were: movement time and accuracy of movement. Of critical interest was the effect that increasing the width of one target in a target pair had on the speed and accuracy of movement to the other target in the pair.

Method

Subjects

Ten male subjects, students in the faculty of Physical Education and Recreation at the University of Alberta, ranging in age from 20 to 28 years, volunteered for the experiment. All subjects wrote with their right hands.

Apparatus and Task

The 16 target pair combinations obtained were constructed by drawing the targets on letter size 50% rag paper. Targets in each pair were separated by an amplitude of 20 cm as measured from the mid-points of each target. The 16 target sheets were plastic laminated for protection. Eight of the 16 combinations were selected randomly and reproduced with amplitude 15 cm. These target pairs were used as practice targets.

Target pairs could be displayed beneath a clear plastic sheet which covered a Summergraphics Supergrid digitizing tablet. The position of the target sheets was fixed using reference markers on both the target sheet and the supergrid. A pen-shaped stylus was

attached to the supergrid and used to collect positional data from the grid. A PDP 10/11 digital laboratory computer was used to sample and store digital data from the supergrid.

Subjects were seated such that the mid-line of the body was aligned with the center of the tapping apparatus. The subjects held the stylus vertically in the right hand in a pen grip fashion. The subject was instructed to keep the stylus vertical at all times during the tapping task. The first of the 8 practice target combinations was positioned beneath the plastic sheet on the digitizing tablet. The order of presentation of the target combinations was determined randomly. The subject was instructed that the task required him to move alternately between the two presented targets as rapidly and accurately as possible, while maintaining contact with the grid.

At the beginning of each movement bout the stylus was positioned above the left hand of the two targets. The subject was presented with a tone by the computer and instructed to commence moving when the tone ceased, producing the first movement to the right hand target and subsequently alternating movements between the targets. The subject was instructed to cease moving when a second tone was heard. During the movement interval the computer was programmed to sample data from the supergrid at a rate of 100 samples per second. Data was sampled and stored by the computer for later analysis.

Following a 15 second period of reciprocal movement the subject rested while the experimenter changed targets. The subject repeated the tapping task with the new target combination. Following presentation of the 8 practice combinations, the 16 test combinations were presented in random order. Stored data was used to calculate values for the following variables for movements to the right and left targets in each target pair: movement time; variable error; constant error; dwell time; time to peak velocity (absolute); time to peak velocity as a percentage of movement time.

Design

All subjects were tested under all treatment conditions. The sixteen treatment conditions were made up of all possible 2 target combinations of left target size (4) X right target size (4).

RESULTS AND DISCUSSION

In four target pair combinations a 1 cm target appears to the subject's right and is paired with a 1, 2, 4, or 8 cm target respectively. Similarly, for the 2 cm target, there are four target pair combinations in which the 2 cm target appears to the subject's right when paired with a 1, 2, 4, or 8 cm target. This is also the case for the 4 cm and 8 cm targets. Equally, there are for target pair combinations in which the 1 cm target appears to the subject's left when paired with a 1, 2, 4, or 8 cm target. The same is true for the 2, 4, and 8 cm targets.

Mean movement times for movements performed to the subject's right are displayed in Figure 1 as a function of the paired (left) target size. Analysis of variance resulted in significant main effects being identified for right target size $F(3,27)=22.34$, $p < .001$ and for paired Target Size $F(3,27)=20.35$, $p < .001$. No other effect was significant. Results indicated that movement time to a target positioned to the subject's right decreased as the size of the paired target (left) increased. Furthermore, as the size of the right target increased movement times to that target decreased.

A similar analysis was performed on error data. Mean variable error for movements performed to targets on the subject's right are displayed in Figure 2 as a function of paired (left) target size. Analysis of variance resulted in significant main effects being identified for right target size $F(3,27)=6.10$, $p < .01$ and for paired target size $F(3,27)=26.27$, $p < .001$. A significant right target X left target interaction was also identified $F(9,81)=2.95$, $p < .01$. These results indicated that as the size of the right target increased, errors on that target also increased. However, as the size of the paired target (left) increased, errors on the targets

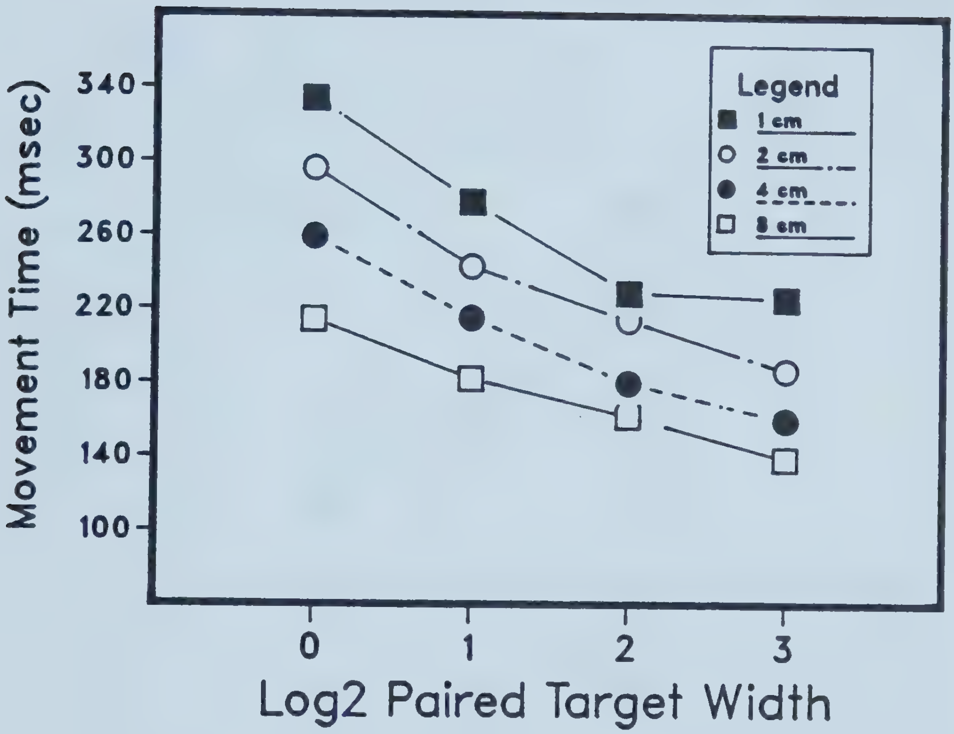

Figure 1. Mean movement time (msec) for movements to the right target as a function of left target width and log2 paired target width.

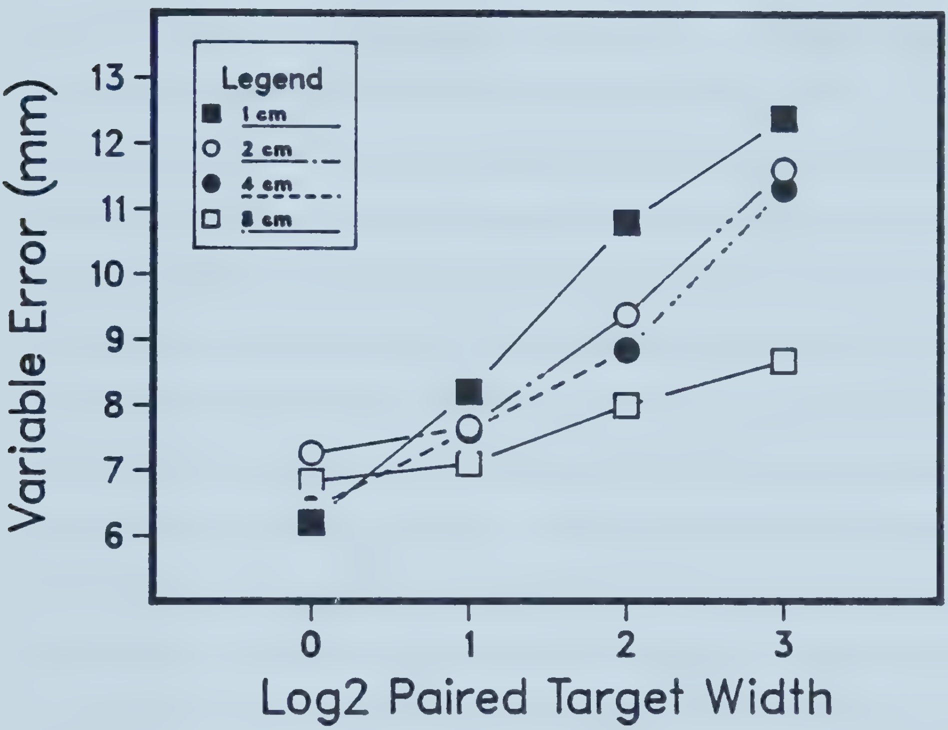

Figure 2. Mean variable error (mm) for movements to the right target as a function of left target width and log2 paired target width.

positioned to the right *decreased* for all target sizes except the 1 cm target which demonstrated no significant change in error as a result of increases in paired target size.

Taken together, these results indicate that as the size of the left hand target in a target pair increased movement times to the right hand target decreased, while, at the same time, errors on the right targets either decreased or remained unchanged. These findings are contrary to current notions of speed-accuracy trade-off since increased speed of movement should have resulted in increased error and this was not the case.

A similar analysis was performed for movements performed to the subject's left. An identical pattern of results was obtained. Movement time and error data are displayed in Figures 3 and 4 respectively. Analysis of variance performed on movement time data resulted in significant main effects being identified for left target size $F(3,27)= 20.80$, $p < .001$ and for paired target size (Right) $F(3,27)=20.32$, $p < .001$. This indicated that as the paired target (right) increased in size, movements to the left target were performed faster. Analysis of variance performed on error data resulted in significant main effects being identified for left target size $F(3,27)=20.09$, $p <.001$ and paired target size $F(3,27)=22.44$, $p < .001$. A significant Left Taregt Size X right target size interaction was also identified $F(9,81)=2.81$, $p < .01$. These results again indicated a decrease in error on the left target as the right target increased in size for all left target sizes except the 1 cm target. In this case there was no significant change in error as a function of paired Target Size (Right).

These results clearly confirmed the original hypothesis that if one target in the reciprocal tapping task is made wider relative to its partner, then movements to the smaller target should be faster and/or more accurate than they would be if the same small target were paired with an equal width target. In all cases examined, except for the 1 cm target, movements actually became *faster* and *more accurate*. In the 1 cm target case, movements became faster but did not change in accuracy. This latter finding, while still demonstrating the hypothesised increase in transmitted information, may be the result of a floor effect for error, in that subjects cannot reduce error any further without significant alteration of their criterion for accuracy.

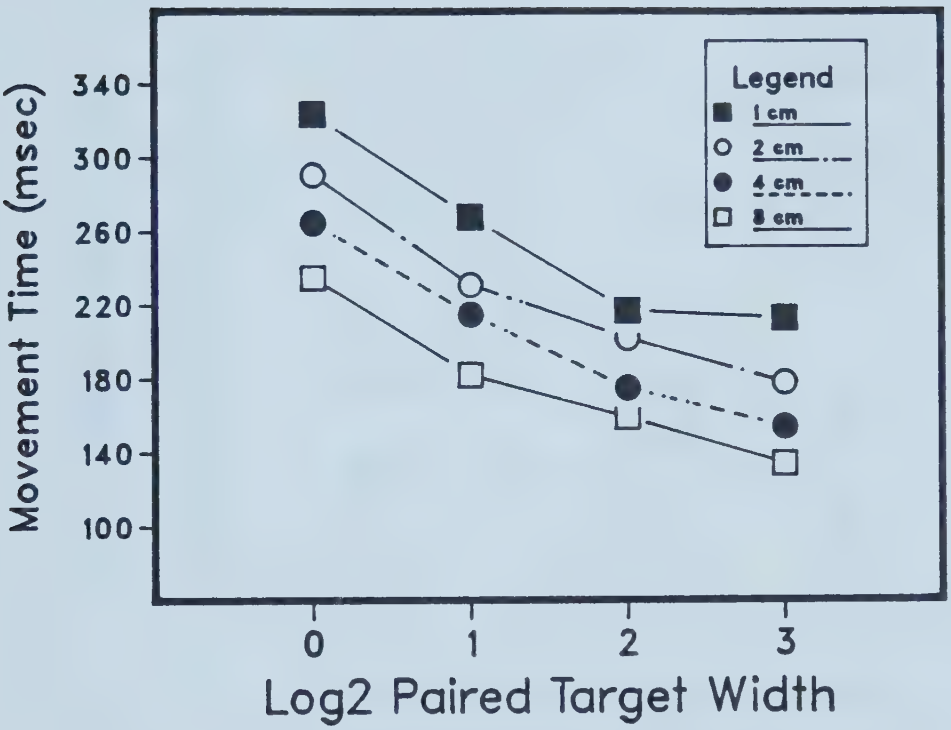

Figure 3. Mean movement time (msec) for movements to the left target as a function of left target width and log2 paired target width.

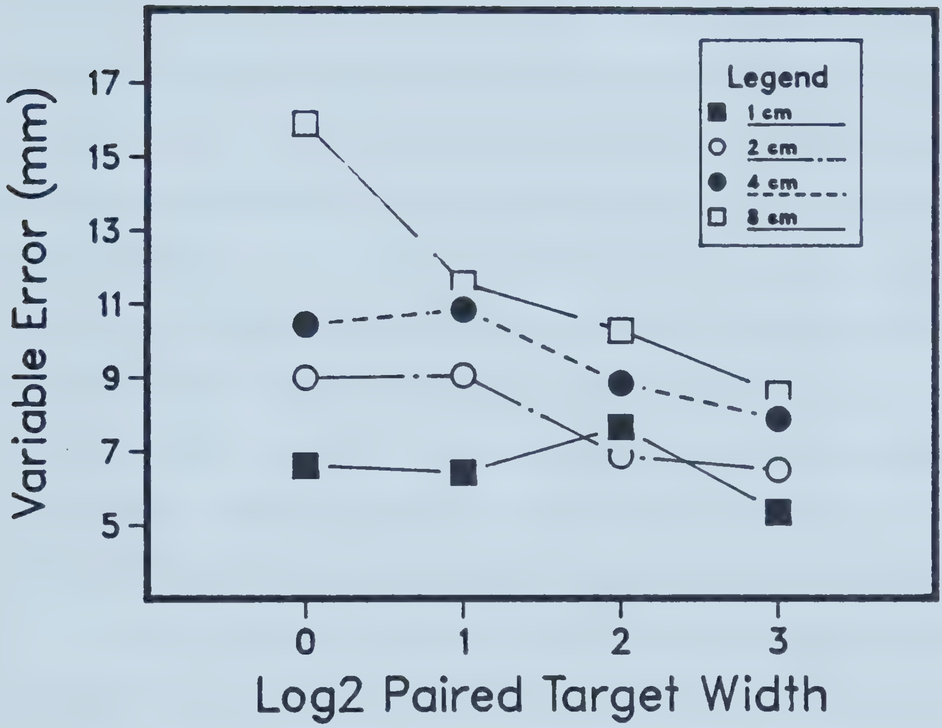

Figure 4. Mean variable error (mm) for movements to the left target as a function of left target width and log2 paired target width.

The possibility exists that the results obtained are the result of the subject adopting different movement times to the left and right targets within a target pair such that movements are made faster and with more error in one direction than the other. To test this possibility analysis of variance was performed on movement time data as a function of condition and direction of movement. A significant main effect for movement condition was observed $F(15,135)=15.79$, $p < .001$ but not for direction of movement or for the interaction between condition and direction. While movement times decreased as a function of increases in target size within a target pair combination, there was a symmetry between left and right movement times. For example, in Condition Four, a 1 cm target is positioned to the subject's right and an 8 cm target to the subject's left. Mean movement times to the right target were 214 msec, while to the left was 224 msec. These movement times were not statistically different, but they were associated with widely different error scores. Error on the 8 cm target was 15.9 mm, while on the 1 cm target was only 6.8 mm. Obviously, while being able to maintain a symmetry of movement times in the left and right directions, the subject is able to manipulate the processes responsible for the control of movement error.

A second possibility to account for the observed changes in speed and accuracy of movement is that in preparing to reverse movement direction subjects dwell longer on more demanding (smaller) targets than they do on less demanding (larger) targets. Since the time spent at rest on the target is a componenet of the movement time, longer movement times could be the result of longer dwell times. Dwell time, in this case is seen as the time the subject remains at zero velocity prior to a movement reversal. Figure 5 shows dwell time as a function of right target size and left target size for movement reversals occuring on the right target. Analysis of variance resulted in significant main effects for right target size $F(3,27)=7.03$, $p < .01$ and for left target size $F(3,27)=5.76$, $p < .01$.

Figure 6 shows dwell time as a function of right target size and left target size for reversals occuring on the left target. Analysis of variance resulted in the same pattern of results being evidenced as for reversals occuring on right targets. Significant main effects for right target size $F(3,27)=3.28$, $p < .01$ and left target size $F(3,27)=3.21$, $p < .01$.

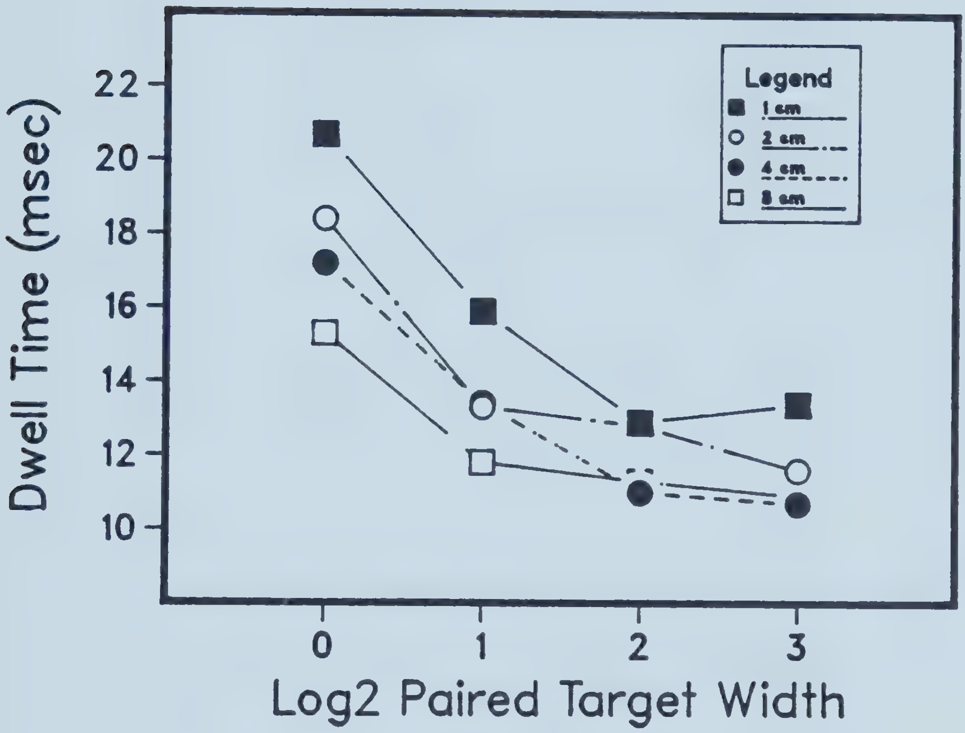

Figure 5. Mean dwell time (msec) following movements to the right target as a function of right target width and log2 paired target width.

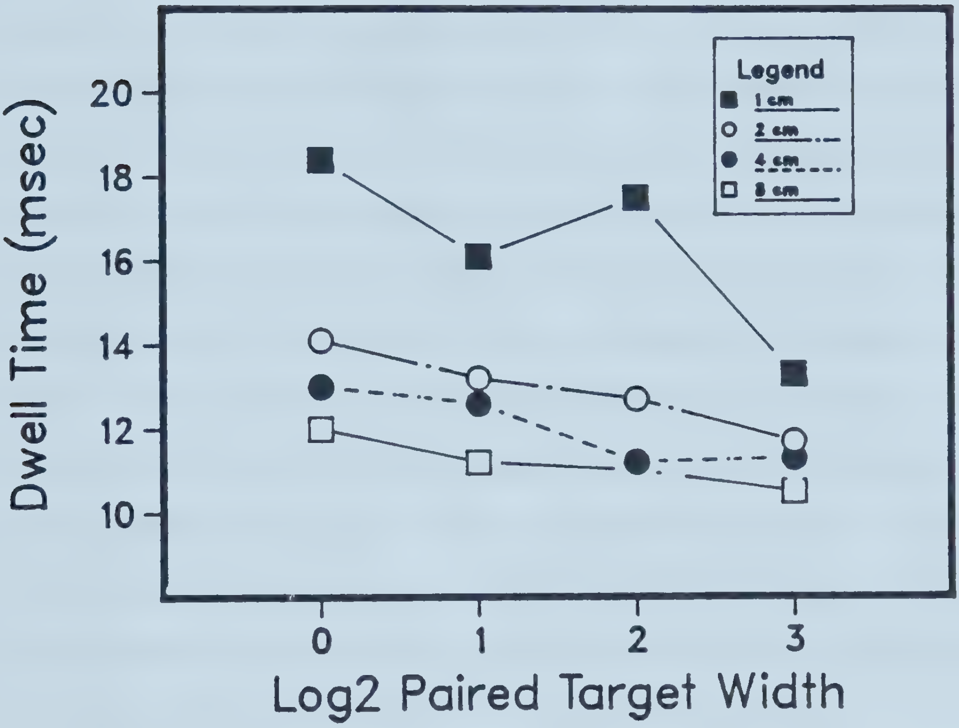

Figure 6. Mean dwell time (msec) following movements to the left target as a function of left target width and log2 paired target width.

These results are interesting for several reasons. The significant main effect for target size, where the target size refers to the size of a target at which the reversal occurs, indicates that it takes longer to reverse a movement when the accuracy requirements for that movement are high rather than low. The importance of the size of the paired target is evidenced by the significant effect for paired target size. As the difficulty of the upcoming movement is reduced the time required to produce the reversal is also reduced. That is, the time taken to reverse a movement on a small target is reduced when that target is paired with a large target rather than another small target. These observations, taken together with the extremely short duration of the dwell times, suggest that dwell time is associated with an evaluation of the accuracy of the just completed movement. The fact that this evaluation takes less time on a small target when it is paired with a large target suggests an attentional bias on the part of subjects. Visual observation of the subject's behavior, during execution of the tapping task, indicated that when a small target was paired with a large target the subject tended to fixate on the small target. When two small targets were paired together, the subject appeared to alternate visual fixations between targets with fixed periodicity. The necessity to alternate between targets appeared to result in increased time for fixation which consequently resulted in increased dwell times.

Dwell time, rather than being responsible for the planning of upcoming movements can be seen to be the time during which subject's collect information relative to the success of the just completed movement. The time required to collect this information is reduced as the size of the target at which the reversal occurrs increases, perhaps because perceptual discrimination is easier on large targets. Dwell time is further reduced on a small target when the necessity to alternate fixations between targets is reduced by making the paired target large.

In order to test the predictive ability of Fitts' Law a correlation and regression analysis was performed between Index of Difficulty (ID) and Movement Time (MT) data. ID was calculated using Welford's correction. (Welford, 1960). For each target size, correlation coefficients and regression parameters were determined between ID and MT for that target

and for the targets with which it appeared. For example, a 1 cm target appeared in four conditions as the right target. Correlation coefficients between ID and MT were determined for movements produced to these 1 cm targets. Similarly, the correlation coefficient between ID and MT for the movements performed to the paired targets (i.e those targets appearing to the subject's left when the 1 cm target appeared to the right) namely the 1, 2, 4, and 8 cm targets. Similar analyses were performed for 2, 4, and 8 cm targets when they appeared to the subject's right. In the following discussion the target which does not vary in size relative to the paired target will be referred to as the fixed target, while the target which increases in size will be referred to as the variable target.

Figure 7 shows results of regression analysis peformed on ID and MT data for Fixed Target sizes 1, 2, 4, and 8 cm when the fixed target appeared to the subject's right. Figure 8 shows the same analysis performed when the fixed target appeared to the subject's left.

For all fixed target sizes the correlation between ID and MT for movements performed to the variable targets was consistently high and positive. That is, as ID increased MT increased. Regression equations are shown in the Figures for each line represented. For variable targets Fitts Law accounted for 99, 89, 86 and 84% of total variance for fixed target sizes 1, 2, 4, and 8 cm respectively, when the fixed target appeared to the Subject's right. When the fixed target appeared to the subject's left Fitts' Law accounted for 97, 90, 92 and 93% of the variance observed on the variable targets when paired with fixed targets of 1, 2, 4, and 8 cm respectively. These results would be expected on the basis of Fitts' Law since as the accuracy constraints were reduced by making the target larger, information was reduced and, subsequently, movement time decreased.

Of more interest was the observed relationship between ID and MT for movements to the fixed targets. For all fixed target sizes except the 1 cm target there was a consistently high *negative* correlation between ID and MT when the fixed targets appeared to the subject's right and when they appeared to the subject's left. When the fixed target appeared to the subject's right Fitts' Law accounted for 99, 90 and 74 % of the total variance observed on performance to fixed targets of 2, 4, and 8 cm respectively. Similarly, when the fixed target appeared to

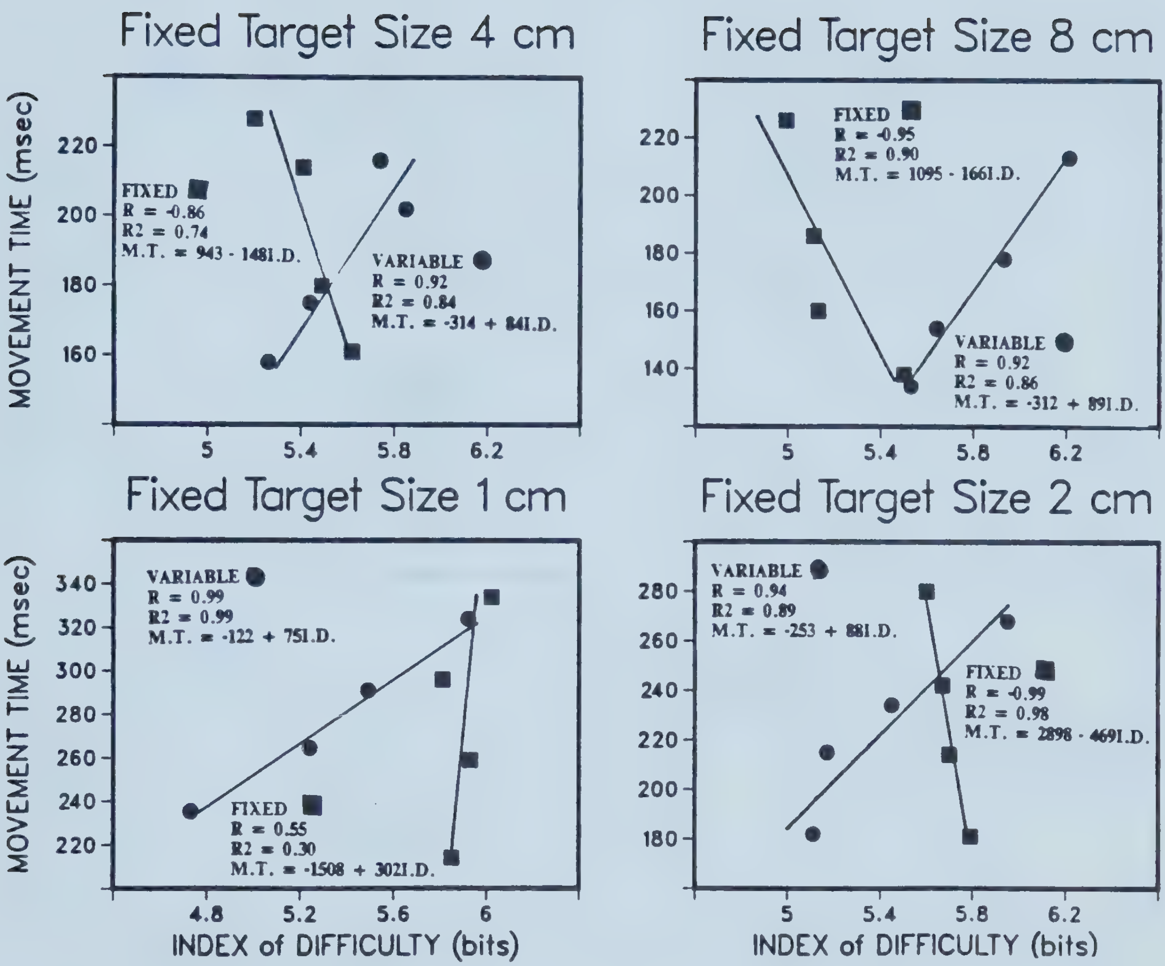

Figure 7. Movement time (msec) as a function of index of difficulty for fixed and variable targets for each fixed target width, when the fixed target appears to the subject's right.

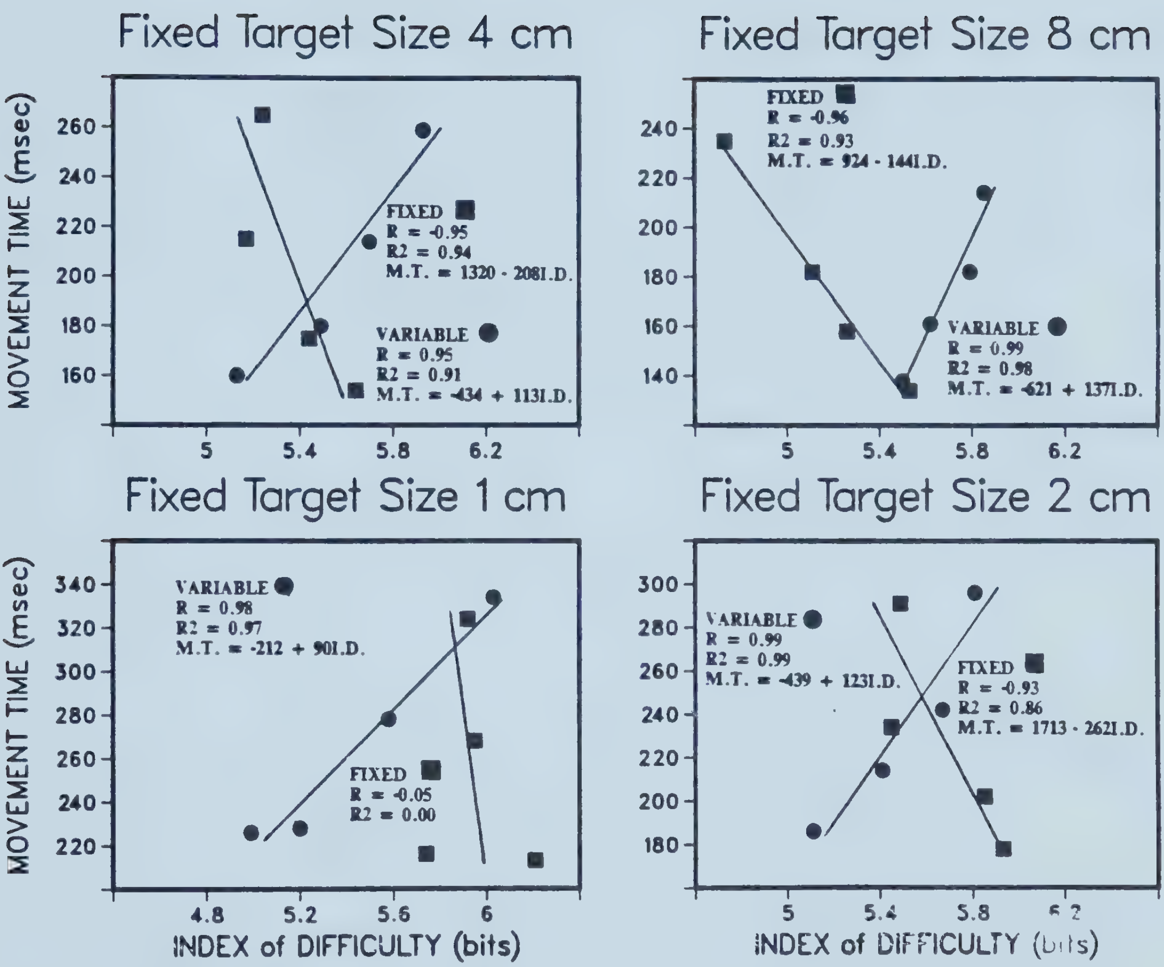

Figure 8. Movement time (msec) as a function of index of difficulty for fixed and variable targets for each fixed target width, when the fixed target appears to the subject's left.

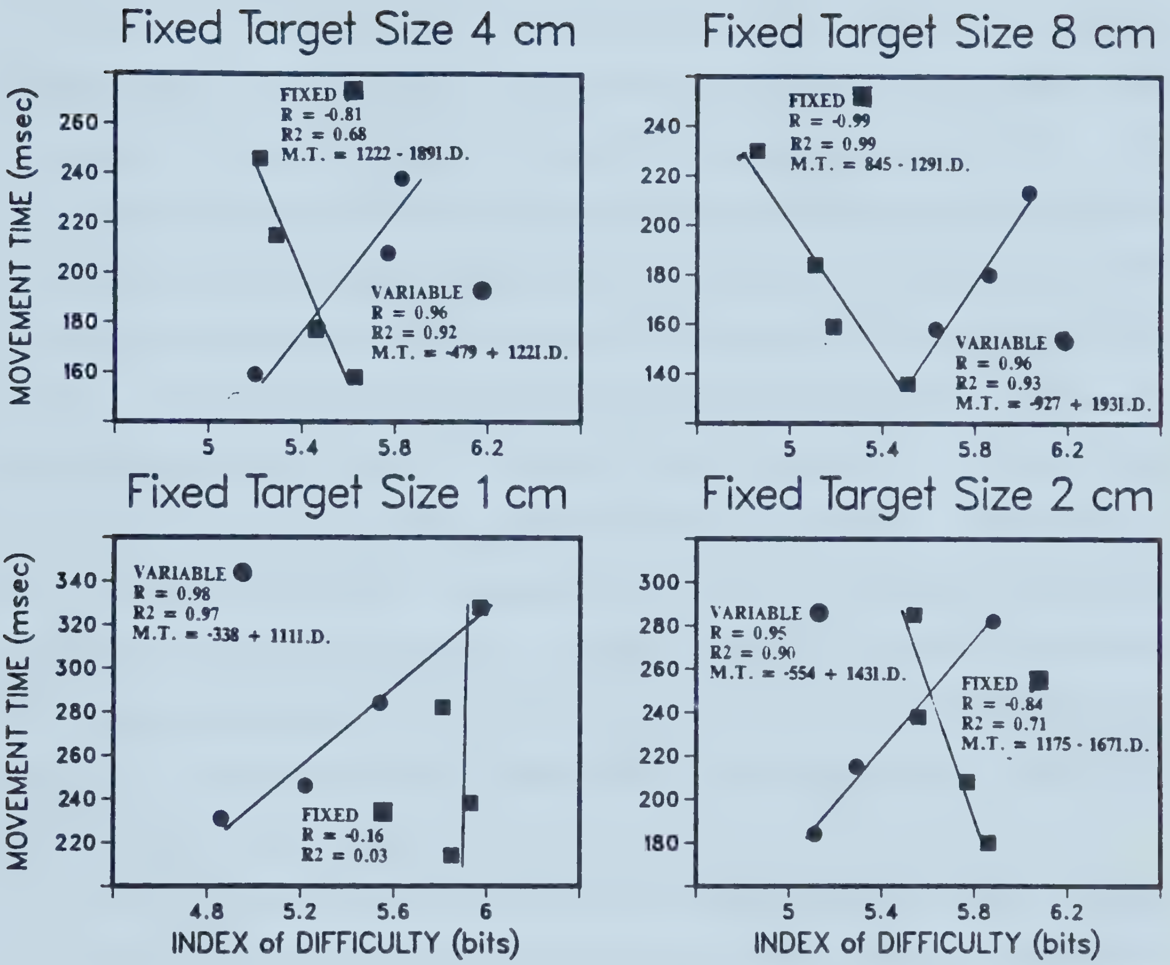

Figure 9. Movement time (msec) as a function of Index of Difficulty for fixed and variable targets for each fixed target width, independent of the position of the fixed target.

the left, Fitts' Law accounted for 90, 70 and 99 % of variance for fixed target sizes of 2, 4, and 8 cm respectively. The low correlations observed in the 1 cm target condition were indicative of the floor effects described earlier.

Figure 9 shows MT as a function of ID for the fixed and variable targets independent of target position. That is, the mean of the left and right positions. For performance to the fixed targets Fitts' Law accounted for 86, 94 and 93 % of variance.

These results are somewhat at odds to Fitts' Law since in this case, the increases in ID were associated with decreases in movement time. For 2, 4, and 8 cm targets the decreases in movement time observed were linearly related to the increases in ID. This finding points quite clearly to a trade off in performance between left and right targets within a target pair. As the demand associated with one of the targets in a pair was reduced by making that target larger, performance to the smaller target improved. This increase in performance was evidenced by increased speed and increased accuracy of movement. The fact that the demand associated with any given target was linearly related to the size of the target was evidenced by the extremely high negative correlation observed between ID and MT for performance to the fixed targets. This suggests that as variable target size increases there is a predictable and proportional increase in performance to the fixed target.

The importance of these findings can be summarized as follows. Within a target pair, as one target increases in size relative to its partner which remains fixed, the necessity for the subject to monitor feedback information relative to larger target is reduced. As a result, the subject is able to devote more resources to the control and evaluation of movements to the smaller fixed target, with the result that performance improves for movements to the fixed target.

The current interpretation of the processes underlying the trade off between speed and accuracy of movement would suggest that when the subject is performing within unequal target pairs he is able to produce movements in one direction using processes which are different from those he employs for movements in the opposite direction. Symmetrical movement times can, therefore, be associated with extremely different errors. The apparent

dissociation between movement time and errors may the result of different control processes being employed to control movements in different directions. Movements to large targets, requiring little monitoring of feedback, could be under programmed control and place little demand on the subject, while still maintaing a relatively high degree of accuracy (Wallace and Newell, 1983). This decrease in demand would allow the subject to devote more resources to the performance of the more demanding feedback dependent movements to the small targets. The greater the availability of resources, the faster and more accurate the movements.

If the above argument is valid then differences in movement profiles might be expected for movements which are performed in the same time to different sized targets. That is to say, while a global parameter such as movement time may appear to show no difference for left and right movements to targets of different sizes, the processes which produce these equal movement times my be somewhat different.

In the current experiment, the variable chosen to reflect differences in movement profiles was time to peak velocity expressed as a percentage of total movement time. The time at which peak velocity occurs is indicative of the time at which the initial impulse producing phase of the movement gives way to subsequent control processes (Zelaznik, Schmidt and Gielen). Differences in the time at which peak velocity occurs may reflect the adoption of different control strategies by the subject. Figures 10 and 11 show time to peak velocity expressed as a percentage of total movement time as a function of right target size and left target size for movements performed to the Right and Left respectively.

Analysis of variance performed on time to peak velocity data for movements performed to the subject's right resulted in significant main effects being identified for the variables right target size $F(3,27)=5.61$, $p < .01$ and paired target size (left) $F(3,27)=9.32$, $p < .01$. No other effect was significant.

The results suggested that when subjects performed movements away from the body mid-line (to the right) that the time required to reach peak velocity was a function of both the size of the aimed for target as well as the size of the target from which the subject was moving. The smaller the aimed for target, the earlier the subject reached peak velocity. This

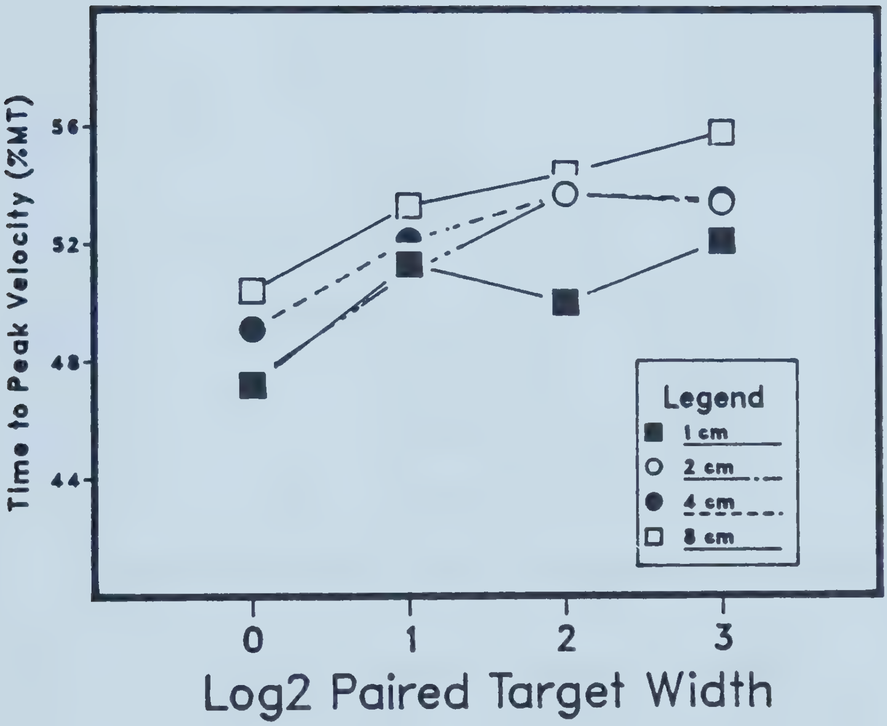

Figure 10. Mean time to peak velocity (% total movement time) for movements to the right target as a function of left target width and log2 paired target width.

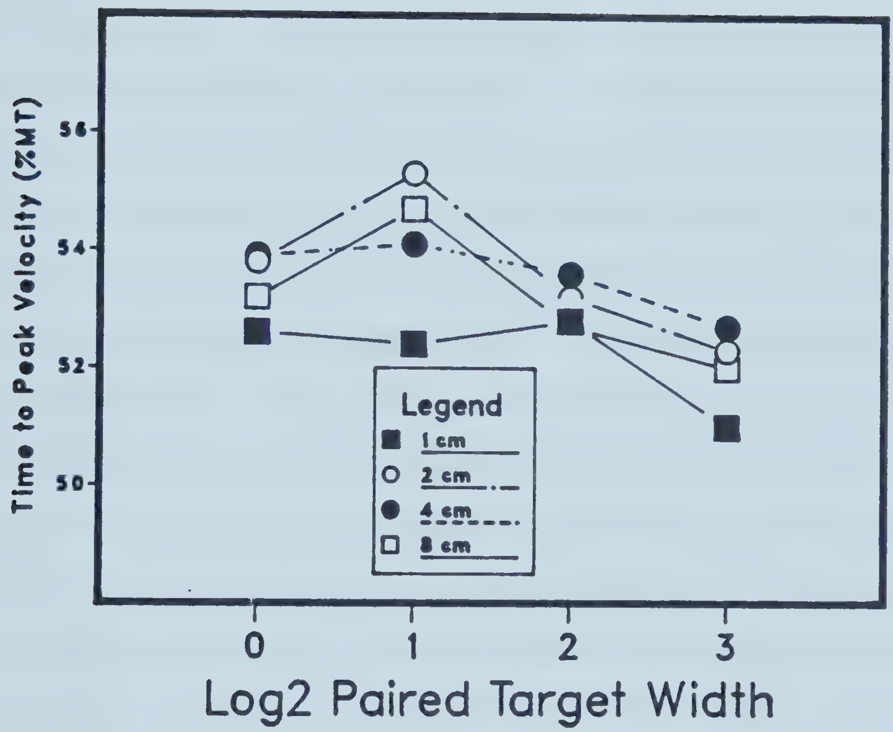

Figure 11. Mean time to peak velocity (% total movement time) for movements to the left target as a function of left target width and log2 paired target width.

effect was moderated by the size of the paired target such that as the size of this target increased, peak velocity of movement was achieved later.

The above findings held only for movements performed away from the mid-line. For movements towards the mid-line the subject showed no significant differences in the time at which peak velocity was achieved as a function of the size of the aimed for target or the size of the paired target. These findings were not surprising, however, since the localization of targets and the production of movement is more efficient when the movements are made towards the midline rather than away. For movements directed away from the mid-line it was clear that subjects adopted different control strategies according to the demand of the task (small targets resulted in earlier peak velocity), and on the availability of resources (increasing paired target size resulted in peak velocity to the aimed for target occuring later). It appeared therefore, that although movement times could be equal, the processes that produced these movement times could be markedly different. The result of this difference was that the observed errors were also different. Schmidt et al. (1986) suggest that when task demands are altered, by changing the amplitude of movement or movement time, that "the generalized motor program produces a change in the scale but not in the form of the movements kinematic and kinetetic, qualities." (p. 354). Such a proposition would suggest that the time to peak velocity should be directly related to movement time. In the current experiment, for movements made away from the mid-line of the body, there appeared to be a strong relationship between the time that peak velocity was achieved and movement time. However, for movements made towards the mid-line this relationship did not appear to hold. It is suggested that the observed differences in the movement profiles were the result of placing uneven demands on resources by combining targets of unequal sizes and also because of increased efficiency of production of movements towards the body mid-line compared with movements away from the mid-line.

The results of the current experiment cast new light on the relationship between speed and accuracy of movement production. Current theory about the nature of the speed-accuracy trade-off function has been derived from experiments in which the subject is able to devote

all available resources to the acquisition of a single target (as in the single aiming tasks of Schmidt et al.(1978, 1979)), or is required to divide resources *equally* between two targets of equal width separated by some fixed amplitude (as in the tasks of Fitts (1954)). Assuming that subjects work at full capacity at all times, any manipulation of task parameters which results in increased demand on the subject would result in movements of reduced speed and/or increased error. Since the demand in the reciprocal tapping task is increased equally for both targets, then decrements in performance would be expected on both targets, leading to the generally observed relationship between speed and accuracy.

In the current experiment, the demands associated with the two targets in a target pair are manipulated independently. This allows the experimenter to vary the demand associated with one target relative to its partner. This manipulation had several effects. First, increasing the size of one target, relative to its partner which remained fixed, resulted in movements to the fixed target which were both faster and more accurate. While the observed data were accommodated well by Fitts' Law, the slope of the function relating movement time to index of difficulty was negative. As Index of Difficulty increased, movement time decreased. This finding is completely opposite to that expected from a strict interpretation of Fitts' Law.

An examination of dwell time and time to peak velocity data demonstrated that subjects were able to perform movements of equal duration using different control strategies. More demanding movements to the smaller targets reached peak velocity sooner than less demanding movements to the larger targets, when those targets appeared to the subject's right and required movements away from the body mid-line. Movements away from the body mid-line were more demanding on the subject since the subject lacks the spatial frame of reference provided by the body mid-line. As a result, movements away from the mid-line were associated with shorter distance covering phases, indicated by the fact that they reached peak velocity earlier than movements performed towards the body mid-line, and prolonged control stages.

The importance of partitioning resources between the targets within a target pair was evidenced by the consistent effect that paired target size had on performance to the fixed

target. As the size of the paired target increased peformance on the fixed target improved for all measured dimensions. The demand associated with any target was fixed and any resources that were freed as a result of making one of a target pair larger relative to its partner could be devoted to achieving the paired target. This suggestion was supported by the strong positive correlation between movement time and index of difficulty when performance on variable targets was viewed compared with the equally strong *negative* correlation between movement time and index of difficulty when performance on the fixed target was viewed.

In conclusion, the linear speed-accuracy trade-off functions described in formulations such as those of Fitts (1954) and Schmidt et al. (1978, 1979) may merely be special cases of a more fundamental trade-off between performance and resource demand. Trade-offs of the sort described by Fitts (1954) and Schmidt et al. (1978,1979) can only occur when the total resources are devoted to the acquisition of a single target (Schmidt et al.) or when the demand associated with both targets in a target pair is manipulated equally (Fitts). In more realistic situations, where subjects must handle many simultaneous events of differing demand, the trade-off functions observed between the speed and accuracy of movement are dependent upon the partitioning of the resources between events, with increases in resource availability resulting in faster and more accurate peformance.

3. EXPERIMENT TWO

In Experiment 1 it was suggested that the relationship observed between speed and accuracy of movement was due, at least in part, on the availability of processing resources. Understanding the nature of the resource limitations that lead to diminished performance is important to our understanding of the performance of many physical skills. While Experiment 1 offered a new way of observing movement, it did not put forward a theory to account for processing limitations. In Experiment 2, the locus of resource limitations and their relationship to performance outcomes was examined.

The task performed in Experiment 1 can be described as one in which the subject is required to match the position of a moving limb with the position of a target located in visual space. According to Howarth and Beggs (1981) the most important strategy in performing such a task is the continual monitoring of movement and the intermittent correction of errors. While the control theory originally developed by Howarth, Beggs and Bowden (1971) dealt with 'errors of aiming' (errors measured perpendicular to the direction of movement) it also has important implications in explaining 'errors of stopping' (errors measured in the same direction as the movement).

Howarth (1978) has argued that it is impossible to know completely the relative positions of different parts of the body or the position of parts of the body relative to objects in the world, due to the enormous computational and memory problems. Because of these limitations one is required to operate with less than complete information, and to seek out more complete information when it is required. The types of information available to control limb movements can arise form different sources. Information can be kinesthetic, arising from receptors in joints and muscles, as well as visual. In the reciprocal tapping task described in Experiment 1, it is possible that information arose from both sources. For example, when a small target was paired with a large target the subject appeared to visually focus on the small target allowing for the continuous synchrony of visual and kinesthetic error information. On the large target, however, the subject checked the position of the hand relative to the target

infrequently. According to Howarth and Beggs (1981) for errors of aiming, when simultaneous vision of the hand and the target is lost, precise information about the relationship between the hand and the target will deteriorate, resulting in increased error. Kinchla and Smyzer (1967) and Holding (1968) have shown that the accuracy of spatial judgements deteriorates as time progresses from the last opportunity to synchronize the visual and the kinesthetic systems. In Experiment 1 it was postulated that as the size of one target in the target pair increases relative to its partner which remains fixed, the neccessity to perform visual checks of movements to the larger target decreases with the result of increasing spatial error. Hay (1978, 1981) offers supporting evidence for this theory by showing that decreases in spatial error in aiming tasks in children are associated with increased incidence of visual monitoring.

Howarth and Beggs (1981) demonstrated that the presence of a second target in an aiming task can cause eye movements to occur between targets. Errors of aiming are larger when the eyes are moving compared to when they are fixed. It would be expected that the more frequent the eye movements the greater is the error for aiming. In Experiment 1 errors on targets of fixed width decreased as the size of the paired target increased in width. Increasing the width of the paired target reduced the frequency of visual fixation on that target. The subject was able to fixate the smaller target for longer periods, thus reducing errors of aiming due to eye movements between the two targets.

If the subject tends to fixate the smaller target in a target pair it might be asked how the subject is able to successfully acquire the larger target without visual monitoring. Thomson (1983) reports that visually guided reaching slows dramatically just prior to acquisition of a target suggesting the performance of corrections at this point. When reaching is performed blind, however, the dramatic slowing of movement is not observed and the movement ends abruptly following the main reach. Similar results have been found in studies of ball catching (Sharp and Whiting, 1974) and even in longer duration events such as long jump (Lee, Lishman and Thomson, 1982).

The type of findings reported above has led to substantial support of a two stage model of visuomotor control (Welford, 1974; Woodworth, 1899). In such a model, control consists of two phases. An initial 'ballistic' or 'programmed' phase is responsible for bringing the limb into the general vicinity of the target, and can be performed with little reliance on visual information. Thomson (1983) reports that such movements are generally accurate to within 1 - 5 degrees of visual angle, an accuracy which may be sufficient for some tasks. When increased accuracy is required, closed-loop visual guidance is neccessary to zero in on the target. It would be possible therefore, to reduce the demand associated with a reciprocal tapping task by increasing the width of one target such that a programmed, ballistic movement is sufficiently accurate to acquire the target.

Further support for this two stage model comes from studies of visuomotor development and neurophysiology (Paillard, 1980). The two phases of movement are paralleled by the 'two visual system' theory of visual system organization (Paillard, 1980; Trevarthen, 1968). In this view, two separate visual channels are responsible for conveying shape and location cues. Paillard (1980) suggests that central vision, which is highly sensitive to position cues, underlies error detection and correction in aiming movements. He proposes that central vision is responsible for encoding information regarding the rate of change of position of the moving hand relative to a stationary target and allows for the operation of corrective feedback. Paillard refers to this channel as the positional channel. Control of the trajectory of the hand relative to the visual axis, when the visual axis is fixed with respect to the target, relies upon the movement cues provided by peripheral vision. Paillard refers to this as the movement channel.

The interaction between the positional and the movement channels has been demonstrated by numerous researchers using a variety of research paradigms. Hay (1978, 1981) in developmental studies of reaching in children, demonstrated that utilization of visual feedback information during movement increases after the age of seven years. Prior to this age, children employ ballistic aiming strategies which are surprisingly accurate. However, utilization of feedback information allows greater tolerance in the ballistic phase without

jeopardizing the final accuracy of the movement.

Further evidence of the importance of both positional and movement channels is given by Paillard (1979) in the study of recalibration of reaching following prismatic displacement; and by Cremieux and Amblard (1978) in investigations of the effects of long term deprivation of input to the 'movement' channel in neonate kittens.

The integration and utilization of visual information appears to offer a framework for explaining the unusual results obtained in Experiment 1. The suggestion is that when a large and a small target are paired together subjects are able to focus most of their resources on the small target and to take advantage of efficient movement correction due to the availability of information from both the 'movement' and 'position' channels and also through the synchronization of visual and kinesthetic cues. Movements to the large targets appear to rely almost entirely on ballistic aiming and information derived exclusively from the movement channels.

Several limitations were evident in Experiment 1. First, only a single amplitude of movement was employed. This amplitude allowed for the possibility that both targets appeared within the subject's visual field with the result that the distinction between positional and movement information was not important to the subject. A second limitation was that positional movements of the subject's eyes were not monitored. This made it impossible to draw any conclusions regarding the relative importance of visual information for movements performed to targets of different sizes.

In Experiment 2, the first experiment was repeated with the following modifications. Three amplitudes of movement were selected, 8 cm, 16 cm, and 32 cm, such that both targets could appear within the visual field at short amplitudes, and outside the visual field at longer amplitudes. Such a manipulation would cast some light on the importance of availability of visual information in performing the task. Five target widths were selected (4, 8, 16, 32, and 64 mm). In all conditions a 4 mm target was positioned to the subject's left. The 4 mm target was paired with a 4, 8, 16, 32, and 64 mm target appearing to the subject's right for each amplitude of movement. This gave a total of 15 movement conditions (amplitude (X3) X

right target size (X5)). In a second modification the subject was required to repeat the tapping experiment while visual fixations were filmed. Unfortunately, due to limitations in equipment, it was not possible to film the subject while collecting data from the digitizing tablet. This obviously introduces a possible limitation in that the relationship between the movement data obtained in the first part of the experiment might not be perfectly matched with the eye movement data obtained in the second part of the experiment. However, since the subject's were repeating the same movement task, and since the patterns of movement data obtained in previous tapping studies employing different apparatus had given results consistent with those obtained in Experiment 1, there is no reason to believe that the subject might behave differently when being filmed.

Experiment 2 was designed to examine the unusual findings of Experiment 1 and to provide support for the idea that the unusual speed-accuracy trade-off functions obtained in Experiment 1 were related to strategies of dividing the visual resources unevenly between targets.

METHOD

Subjects

Ten subjects, students at the University of Alberta, ranging in age from 22 to 28 years, volunteered for the experiment. All subjects wrote with their right hand.

Apparatus and Task

The apparatus and task employed in the first phase of Experiment 2 were the same as those employed in Experiment 1, with the following modifications to target material. Three amplitudes of movement (8, 16, and 32 cm) were employed. Five target widths were selected to serve as targets appearing to the subject's right (4, 8, 16, 32 and 64 mm). This gave a total of 15 amplitude/target width combinations. In all combinations a 4 mm target was positioned to the subject's left. Testing procedures were identical to those employed in Experiment 1.

Eight of the 15 target combinations were selected at random and used during the practice trials.

In the second phase of the experiment subjects were required to repeat the tapping task performed in the first phase, with the following modifications to the tapping apparatus allowing for the filming of eye movements. Target pairs were displayed beneath a clear perspex screen placed over a slightly inclined bench, which replaced the digitizingtablet employed in the first phase. A mirror, measuring 45 cm by 30 cm was positioned 2 cm from the top of the position occupied by the target material. The mirror was supported 15 cm above the inclined bench and angled such that when the subject was normally seated in position to perform the tapping task, the upper part of the subject's head could be viewed through a Panasonic video recorder positioned above the mirror. Order of presentation of target pairs was determined by generating random numbers corresponding to the numbers 1 through 15. The method of presentation and the task performed by the subject was identical to that in phase one of Experiment 2 and to Experiment 1. The video camera was used to film the subject's eyes during performance of the tapping task. The video film was later subjected to frame by frame analysis which allowed the following information to be acquired: frequency of eye movements between targets, duration of fixations on targets, and total time of fixation on each target.

Design

All subjects performed 15 seconds of tapping under all target and amplitude combinations in both phases of the experiment.

RESULTS and DISCUSSION

Mean movement times for movements to the subject's right are displayed in Figure 12 as a function of amplitude and right target size. Analysis of variance performed on right movement time data resulted in significant main effects being identified for the factors amplitude $F(2,18) = 170.07$, $p < .001$; and right target size $F(4,36) = 19.93$, $p < .001$. A

significant amplitude X right target size interaction was also identified $F(8,72) = 3.53$, $p < .01$. A similar pattern of results emerged for movements performed to the subject's left (see Figure 13). Significant main effects for amplitude $F(2,18) = 203.13$, $p < .001$ and right target size $F(4,32) = 26.66$, $p < .001$ were identified and a significant amplitude X right target size interaction $F(8,72) = 3.45$, $p < .01$ was also identified. Tests on the simple main effect of amplitude indicated that differences in the movement time between conditions decreased as the size of the right target increased for both movements to the subject's right and left. Wallace and Newell (1983) demonstrated that for low difficulty movements (less than 4.3 bits) subjects are able to acquire a target using a simple ballistic movement and without the necessity for corrective actions. In the current experiment the 64 mm target gave Indices of Difficulty of 1.3, 2.3 and 3.3 bits at amplitudes of 8, 16 and 32 cm respectively, while the 32 mm target gives indices of difficulty of 2.3, 3.3, and 4.3 bits at amplitudes of 8, 16, and 32 cm respectively. It is not surprising, therefore, that at larger target sizes the differences in movement times between conditions were not as great as they were with smaller target sizes.

Figure 14 shows variable error on right targets as a function of amplitude and right target size. An analysis of variance performed on variable error data for movements to the right target demonstrated significant main effects for amplitude $F(2,18) = 31.35$, $p < .001$ and right target size $F(4,36) = 22.49$, $p < .001$. The amplitude X right target size interaction was also significant $F(8,72) = 3.90$, $p < .01$. Tests on the simple main effects of amplitude were significant at all right target sizes. The significant interaction indicated that the differences between error scores increased as right target size increased. A different pattern of results was evident for movements performed to the left targets (see Figure 15). An analysis of variance performed on the error data for movements to the left target indicated significant main effects for amplitude $F(2,18) = 10.96$, $p < .001$ and right target size $F(4,36) = 6.07$, $p < .01$. The amplitude X right target size interaction was not significant. For movements performed to the right targets there was an increase in errors as the size of the right target increased, while for movements to the left, there was a decrease in errors on the left target as

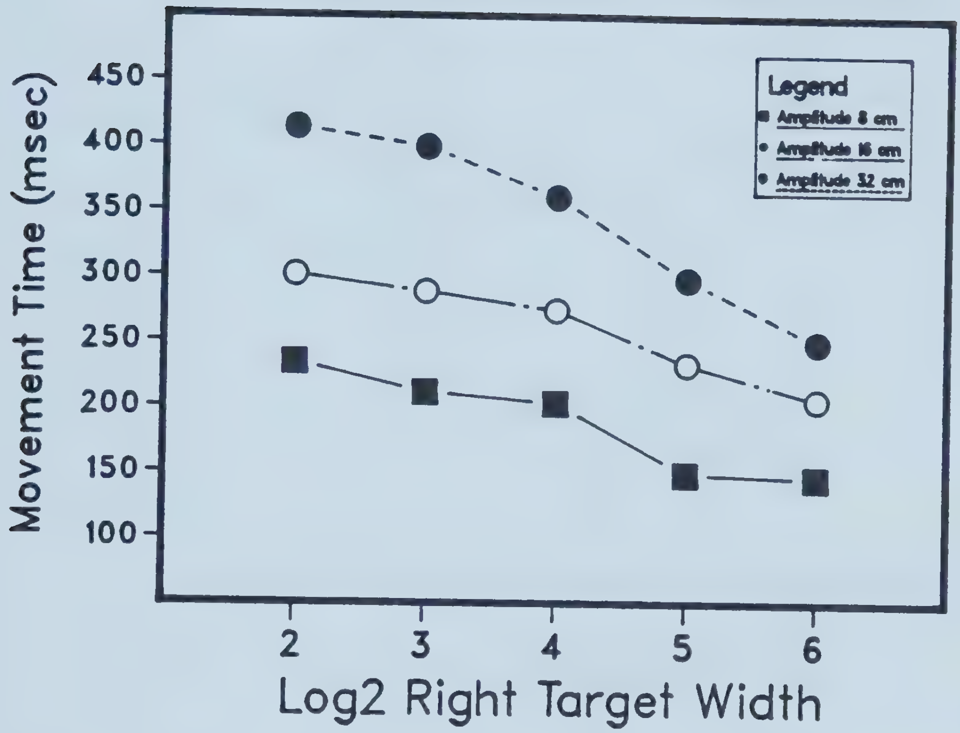

Figure 12. Mean movement times for movements performed to the subject's right as a function of amplitude and right target width.

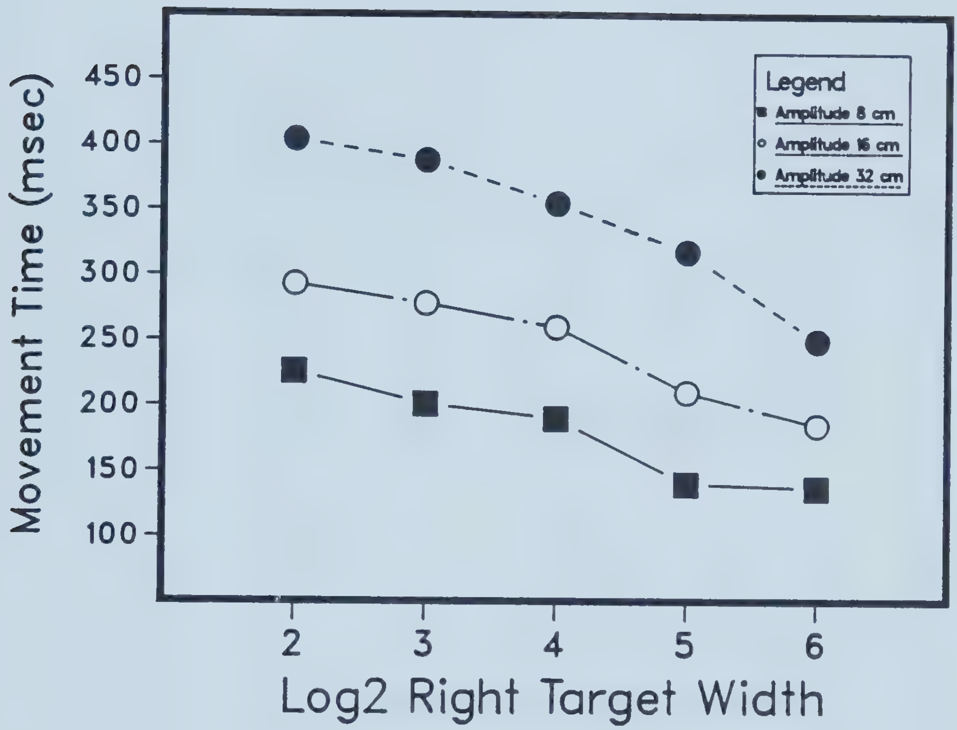

Figure 13. Mean movement times for movements performed to the subject's left as a function of amplitude and right target width.

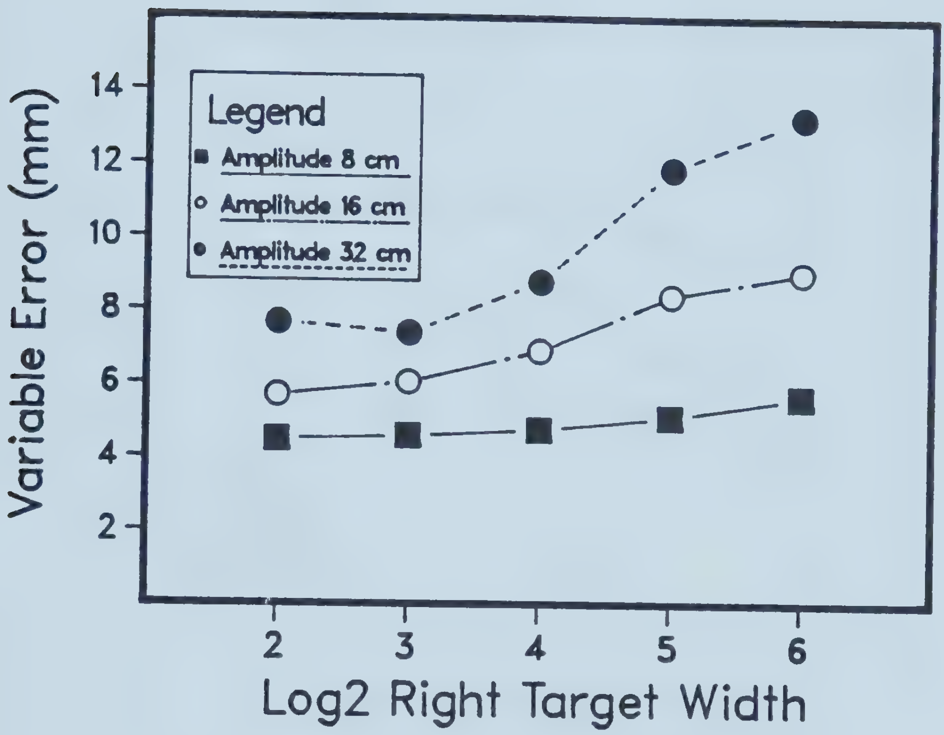

Figure 14. Mean variable error for movements performed to right targets as a function of amplitude and right target width.

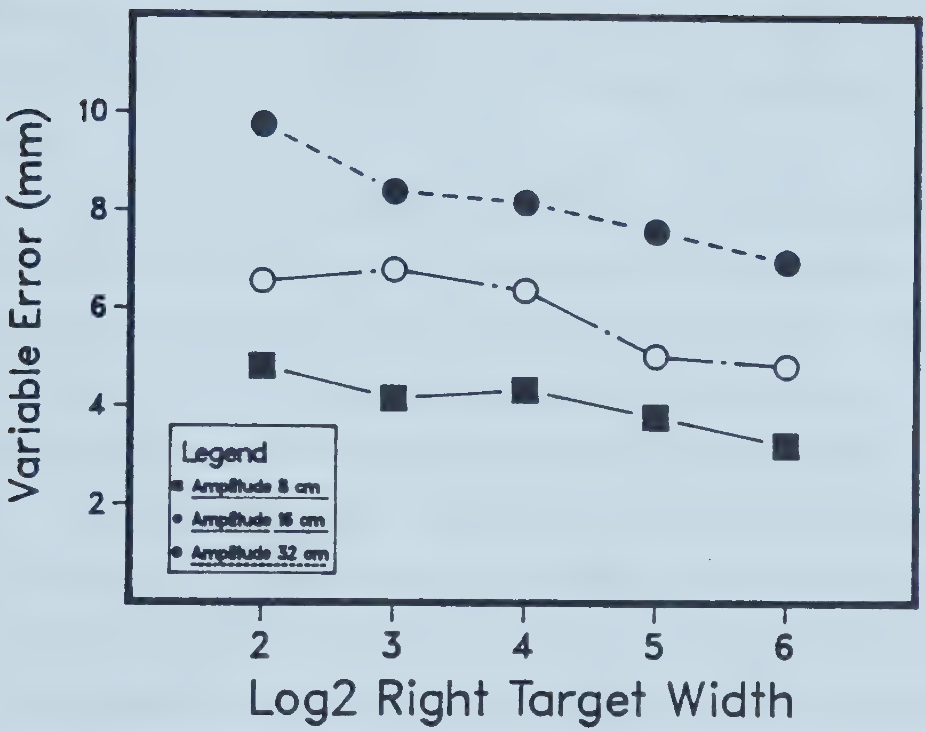

Figure 15. Mean variable error for movements performed to left targets as a function of amplitude and right target width.

the size of the right target increased. The different patterns of errors for movements to the left and right could not be attributed to a difference in movement times for movements to the left and right. An analysis of variance performed on movement time data as a function of direction of movement indicated that movements to the subject's left were consistently faster than those to the subject's right $F(1,9) = 15.25$, $p < .01$. The magnitude of the left/right difference was in the order of 10 msecs with movements to the left being faster than those to the right. Movements to the left are, however, associated with lower error scores than those to the right.

The results of this experiment parallel those of Experiment 1. For each amplitude of movement, increasing the width of the right target in a target pair resulted in faster movements in both the right and left directions (with movements to the left being marginally faster than those to the right). These increases in movement speed were associated with increased error on the right target, but decreased error on the left targets.

The slope and intercept of the straight line function relating movement time to index of difficulty were obtained using linear regression analysis performed at each amplitude of movement for movements to the right and left. Figure 16 shows the results of this analysis for each amplitude of movement for the movements performed to right and left targets. The functions relating ID and MT time are also displayed in the Figure. For 8 cm movements Fitts' Law accounted for 93% of variance for movements to the right, while for 16 and 32 cm movements it accounted for 98% and 96% respectively.

For movements performed to the left Fitts' Law accounted for 80%, 95% and 86% of variance at amplitudes of 8, 16, and 32 cm respectively. The obvious difference between the functions relating ID and MT is that the correlation between ID and MT for movements to the right is consistently high and positive (.93, .98, and .96), while for movements to the left is consistently high and negative (-.89, -.98, and -.93).

These results suggest that the errors observed are dependent upon more than simply the velocity of movement. It appears that if one target in a target pair is increased in width relative to its partner, then movements to the fixed target can be performed faster and more

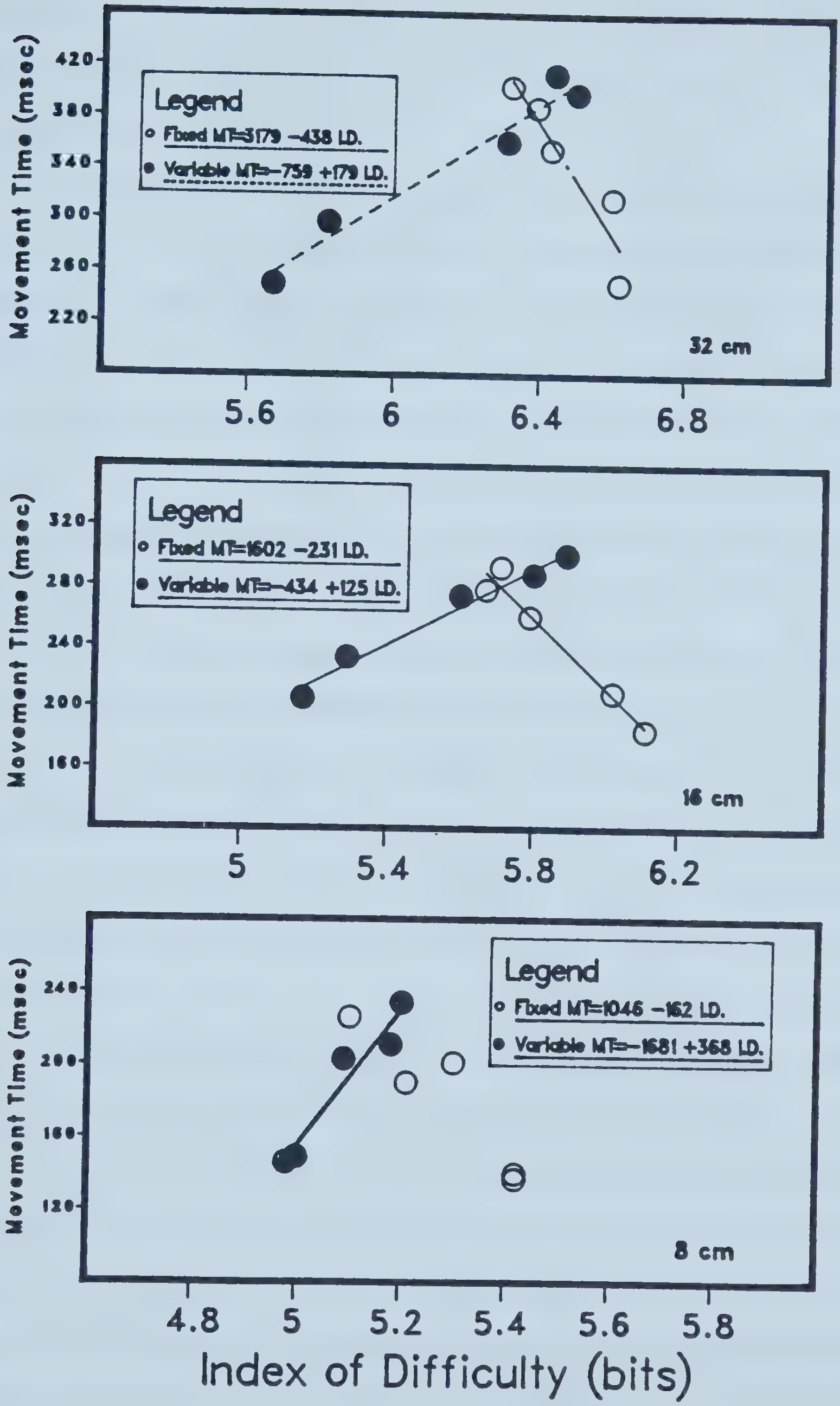

Figure 16. Movement time as a function of Index of Difficulty for movements performed to fixed and variable targets for each amplitude of movement.

accurately than when two equally sized targets are paired together. The increase in speed and the decrease in error on the fixed target appear to be linearly related to the increase in width of the paired target.

It was proposed that the observed increase in performance for movements to the fixed target was the result of subjects being able to devote more performance resources to the acquisition of the fixed target as the target with which it was paired, became larger. It was specifically suggested that these performance resources were associated with the availabilty of visual feedback information and the neccessity to use such information to satisfy the demands of the task. In order to test this possibility, information regarding visual fixation was collected in the second phase of this experiment. Figure 17 shows mean frequency of visual fixations to the left and right, as a function of movement amplitude and the right target width. Unfortunately, it was impossible, using the current methodology, to detect alternations between targets for the 8 cm amplitude target separations. The presented data refer therefore, only to 16 and 32 cm movements. An analysis of variance performed on the frequency of fixation data indicated a significant main effect for the variable right target size $F(1,9) = 304.5$ $p < .001$. As right target size increased the number of visual alternations between targets decreased. No other main effect or interaction was significant. A similar analysis was performed on mean duration of the fixation data. Significant main effects for the variables direction of movement $F(1,9) = 211.1$, $p < .001$, and right target size $F(4,36) = 82.8$, $P < .001$. The direction by right target size interaction was also significant, $F(4,36) = 15.6$, $p < .001$. A test of the simple main effect of direction indicated that the mean fixation times were equivalent when the two targets were equal in size, but that as the right target increased in size the mean fixation time on the left target increased, while that on the right target decreased. The magnitude of the difference between the left and right mean fixation times increased as the size of the right target increased. Hence, as the right target size increased, subjects performed fewer visual checks on that target, and each check was of reduced duration. Figure 18 shows the mean duration of fixation on the left and right targets as a function of amplitude and right target size. Figure 19 shows the total time of fixation on the

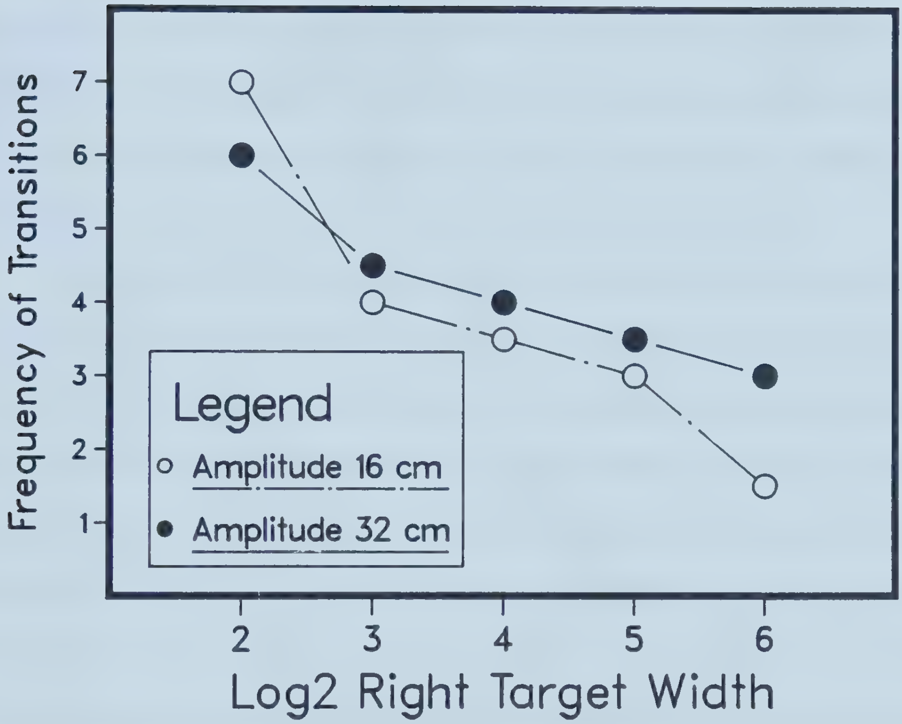

Figure 17. Mean frequency of visual fixation as a function of amplitude and right target width.

left and right targets as a function of amplitude and right target size. An analysis of variance performed on total time data indicated significant main effects for the variables direction of movement $F(1,9) = 3799.2$, $p < .0001$, and right target size $F(4,36) = 17.4$, $p < .001$. The direction of movement by right target size interaction was also significant $F(4,36) = 392.8$, $p < .001$. Tests of simple main effects of direction indicated that the difference in total fixation time was not significant when equal sized targets were paired, but that the differences increased as the right target increased in size. As right target size increased, the total time of fixation on the right targets decreased, while the total time of fixation on the left target increased.

Frequency and duration of visual fixation appear to be important variables in the acquisition of visual feedback information and therefore, in the control of aimed movements. As the width of the right target increased, uncertainty regarding the position of the target decreased and subjects were required to make fewer visual checks in order to ensure the accuracy of peformance in that direction. With fewer visual checks to the right, the subject was able to fixate the left target for increasing periods of time. As a result, movement errors were reduced. Two reasons can be postulated for the reduction in error. Howarth and Beggs (1981) demonstrated that movement errors are less when the eyes are fixed compared to when they are moving. When the subject is not required to alternate fixations and the eyes fixate on one target, errors are reduced. Increasing the duration of fixation, according to Howarth (1978) and Howarth and Beggs (1980), allows for more complete integration of visual and kinesthetic information and also for complete utilization of information provided by movement and position visual channels (Paillard, 1980).

Moray (1984) suggests that information regarding visual fixations is important in determining the attentional strategies adopted by subjects in the acquisition of visual information. These strategies are important because the eyes and, by implication, attention, must be pointed in an appropriate direction to sample a specific source of information. Successful performance is, therefore, based on adopting a strategy which optimizes the acquisition of information. Several models of visual sampling behavior have been developed

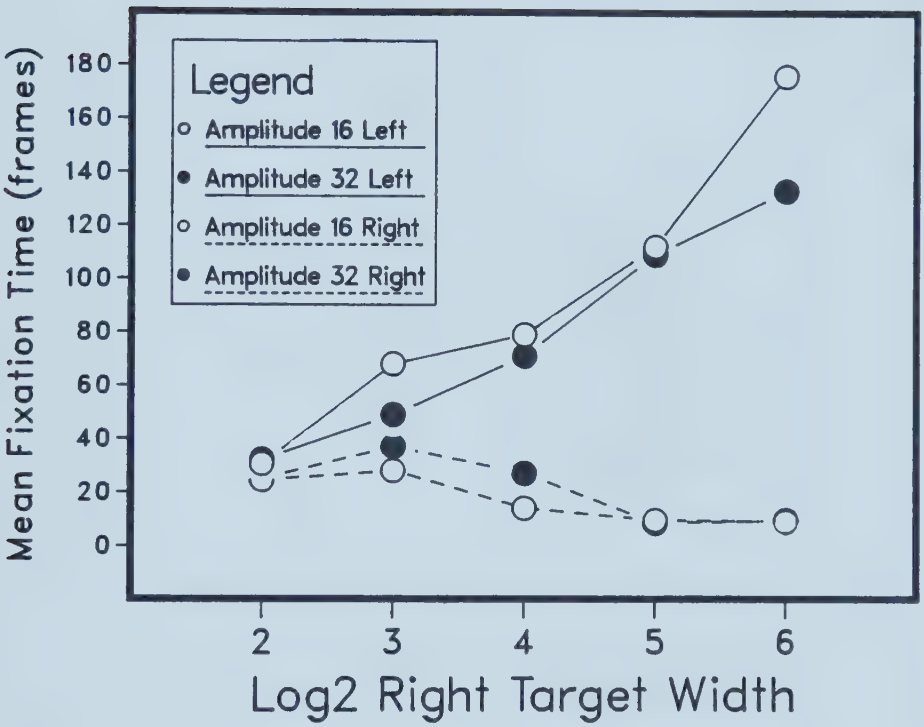

Figure 18. Mean duration of visual fixations to right and left targets as a function of amplitude and right target width.

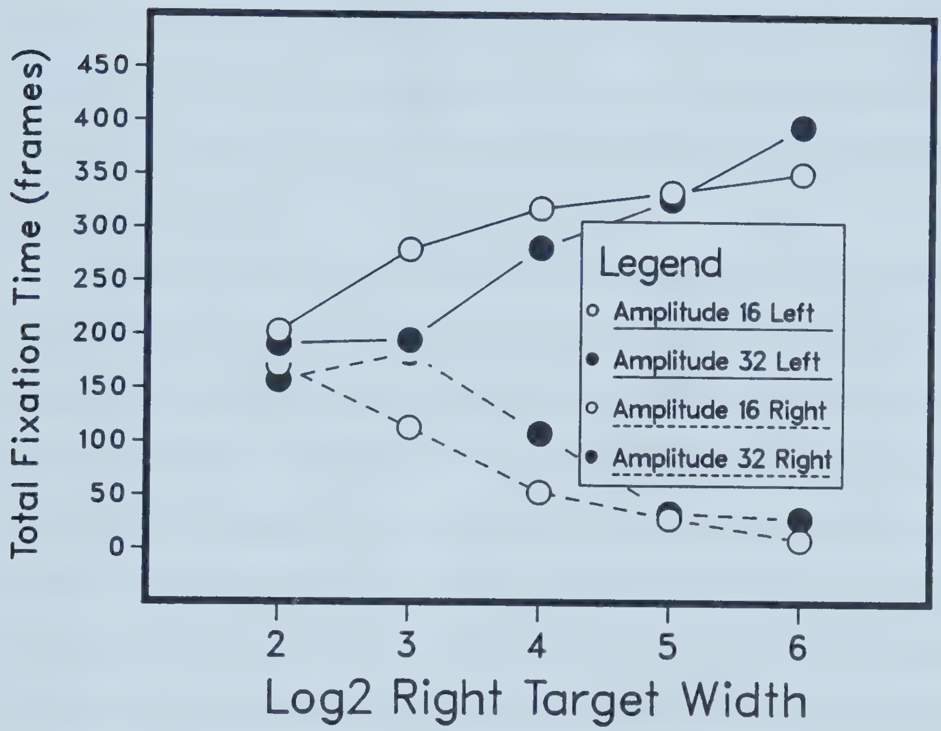

Figure 19. Total time of fixation on left and right targets as a function of amplitude and right target width.

which describe the redirection of attention from one source to another (Sheridan, 1970; Sender, 1970; Kvalseth, 1979; Moray, 1981). Such models are used to predict the optimum frequency and duration of periodic sampling from several information sources and therefore, to determine the extent to which the human operator can continue to be "a successful stable controller despite limits of his or her information due to scanning." (Moray, 1984). The results of this second experiment suggest that subjects do adopt strategies for acquiring information. These strategies appear to be related to the uncertainty associated with each target in the target pair, and, possibly, the relative costs of attending to one target in preference to the other.

Several other variables provide evidence in support of the role of visual fixation in acquiring targets. Figure 20 shows the place at which peak velocity is achieved, as a percentage of the distance moved for movements to the left, while Figure 21 shows the same data for movements to the right. An analysis of variance performed on the position of peak velocity as a percentage of the distance moved as a function of the direction of movement and condition, demonstrated that movements to the left reach peak velocity later (i.e. closer to the target) than movements to the right $F(1,9) = 21.59$, $p < .001$. On average, movements to the left achieve peak velocity after having covered 56% of the total movement distance, while movements to the right achieve peak velocity after only 48% of the movement.

A similar pattern of results was obtained for the variable time to peak velocity as a percentage of the total movement time (see Figures 22 and 23). An analysis of variance demonstrated that movements to the left reached peak velocity after apporroximately 55% of the total movement time, while those to the right reach peak velocity after only 49% of the total movement time $F(1,9) = 15.07$, $p < .001$. An analysis of variance performed on the position of peak velocity data for movements to the fixed 4 mm target positioned to the subject's left resulted in a significant main effect for right target size being identified $F(4,36) = 4.34$, $p < .01$. As the right target increased in width the peak velocity of movement to the left target shifted closer to the target. No other main effect or interaction was significant, indicating that the location of peak velocity was independent of the amplitude of the

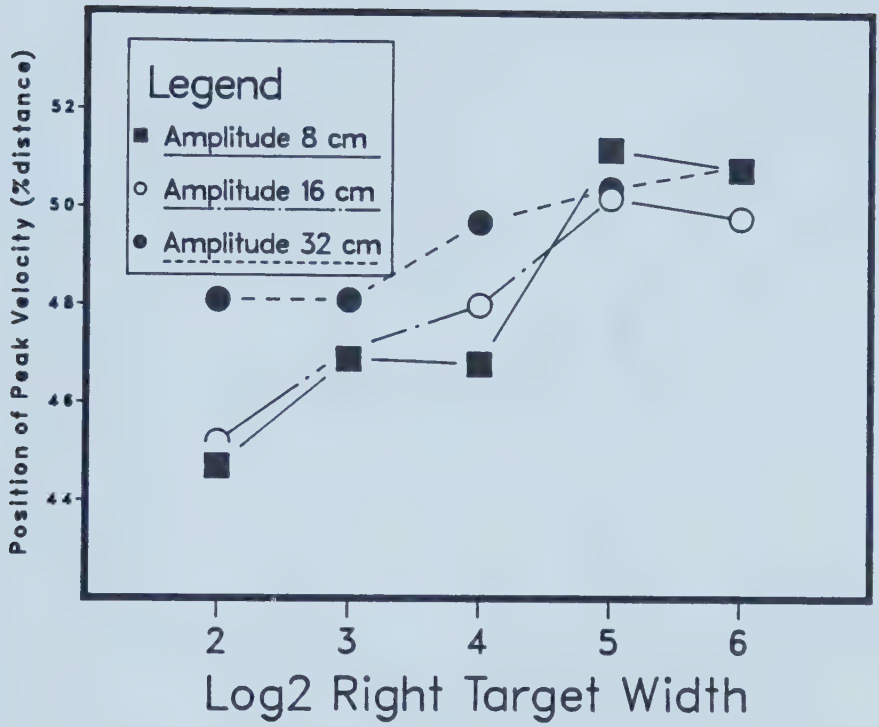

Figure 20. Position of peak velocity as a percentage of distance moved for movements to the right as a function of amplitude and right target width.

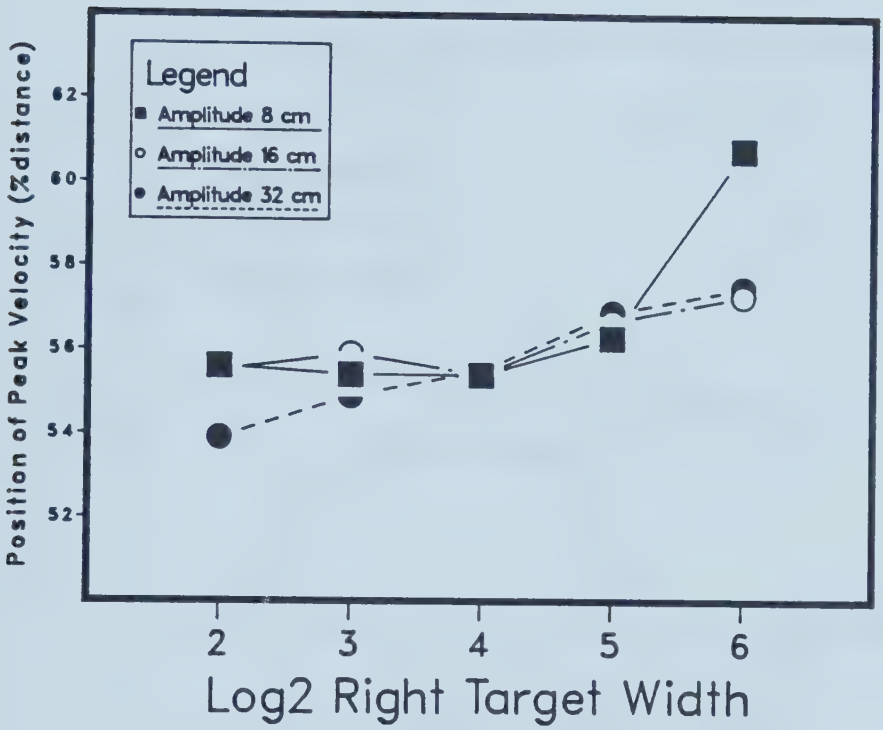

Figure 21. Position of peak velocity as a percentage of distance moved for movements to the left as a function of amplitude and right target width.

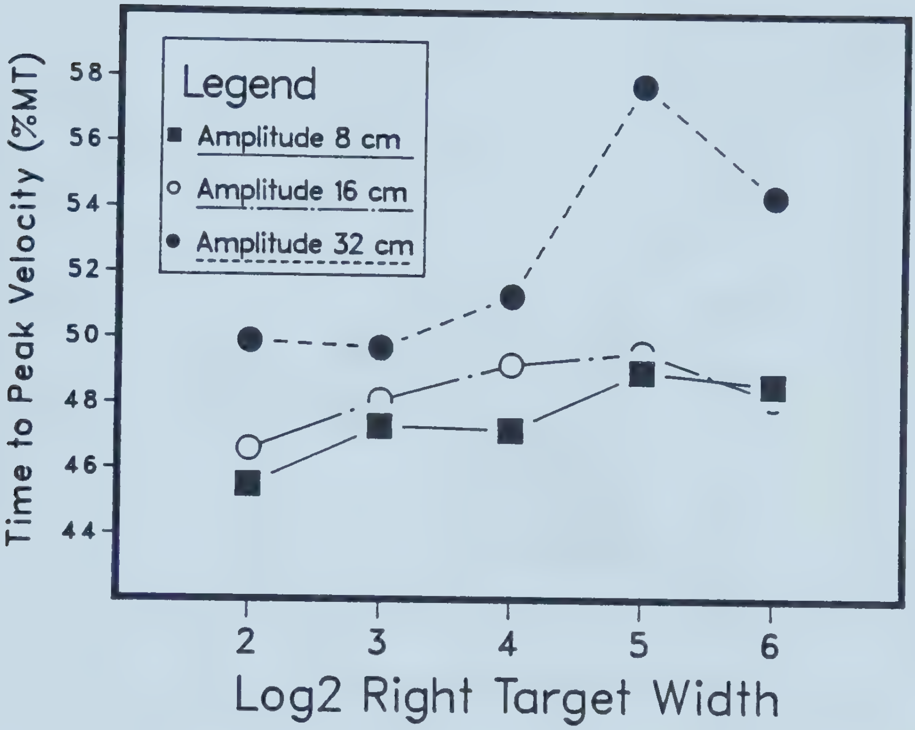

Figure 22. Time to peak velocity as a percentage of total movement time for movements to the right as a function of amplitude and right target width.

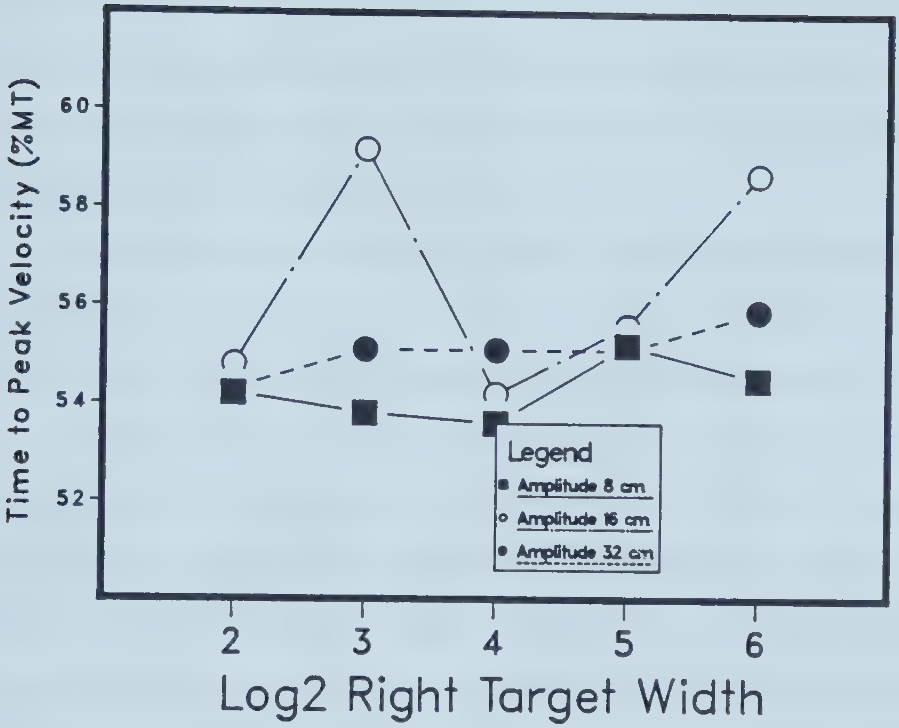

Figure 23. Time to peak velocity as a percentage of total movement time for movements to the left as a function of amplitude and right target width.

movement. For the variable time to peak velocity, neither the main effect for amplitude or right target size was significant. Regardless of the right target size, or the amplitude of movement, peak velocity for movements to the left target occurred at approximately 55% of the total movement time. The effect of increasing the width of the right target was to produce movements to the left target which reached peak velocity closer to the aimed for target at approximately the same relative time. This effect was not influenced by amplitude of movement. Howarth and Beggs (1981, 1985) suggested that the observed errors were the result of the subject's efforts to get as close to the aimed for target as possible before the last correction to the movement had to be made.

Movements to the variable right target showed a slightly different pattern of results. As in movements to the left target, an analysis of variance performed on the position of peak velocity resulted in a significant main effect for right target size being identified $F(4,36) = 8.53$, $p < .01$. As the right target size increased, peak velocity was achieved closer to the aimed for target. No other main effect or interaction was significant. For the variable time to peak velocity, significant main effects were identified for the variables right target size $F(4,36) = 3.32$, $p < .05$ and amplitude $F(2,18) = 7.9$, $p < .01$. As right target size and amplitude increased peak velocity was achieved later in the movement. The rescalability assumption proposed by Zelaznick et al. (1986) appears, in this current experiment to be dependent upon the direction of movement.

An analysis of variance performed on the peak velocity data as a function of direction of movement and condition resulted in significant main effects for the factors direction of movement $F(1,9) = 45.03$, $p < .01$ and condition $F(14,126) = 54.56$, $p < .001$. A significant direction by condition interaction was also observed $F(14,126) = 12.23$, $p < .001$. Tests of the simple main effects performed on the variable direction of movement indicated that movements to the left reached higher peak velocities in all conditions and that this effect increased as the amplitude of movement increased.

To summarize, movements to the fixed left target achieve higher peak velocities than movements to the right, at positions nearer to the aimed for target (this position moves

nearer to the target as the size of the right target increases), in a fixed percentage of the total movement time, which appears to be independent of the amplitude of movement and size of the right target. Peak velocity for movements to the left increases as a function of right target size $F(4,36) = 26.0$, $p < .001$, but this increase is associated with a decrease in errors. For movements to the right, peak velocity increases with the size of the right target $F(4,36) = 18.34$, $p < .001$ but this increase in velocity is associated with increased error. For movements to the right, the time to peak velocity is influenced by both the amplitude of movement and the right target size, with peak velocity occurring later as amplitude and right target size increase. The position at which the peak velocity occurs for movements to the right is affected only by the size of the right target, occurring closer to the target as the target increased in width.

Movements to the left are performed marginally, but significantly, faster than movements to the right. Movements to the left, however, displayed peak velocities which were greater than those for movements to the right. The fact that left/ right movement times differ only marginally indicates that movements to the left have a more important control phase responsible for the rapid slowing of movement, than do movements to the right. This is evidenced by the fact that for movements to the left, the subject is required to slow to zero, a faster movement in a proportionally shorter time than he does when moving to the right. Not only is he able to do this, but he is able to do it while at the same time performing movements which are more accurate. The ability to perform the required corrections appears to be intimately linked with the frequency and duration of visual fixations.

4. EXPERIMENT THREE

Experiments 1 and 2 demonstrated the importance of partitioning resources between targets in reciprocal tapping tasks. As the subject was able to increase the time that one target in a pair was fixated performance to that target became faster and more accurate. It appeared that the availability and processing of visual feedback information was crucial in performing the task. The performance constraints applied in the Fitts' type reciprocal tapping task are considerably different from those encountered in single aiming tasks, where the subject is presented with only single targets. Schmidt, Zelaznick, Hawkins, Frank and Quinn (1979) demonstrated that Fitts' Law did not hold for rapid single aiming movements performed in less than a simple reaction time (< 200 msec). They concluded that such movements were under programmed control, and did not require visually mediated feedback corrections for successful performance. The variability associated with the production of such movements was thought to be related to the magnitude and duration of impulsive forces required to produce the movements. Schmidt et al. formulated a linear speed-accuracy trade-off function which accommodated rapid movements of the single aiming variety but which could not cope with the variability associated with slow reciprocal movements encountered in Fitts' task. Wright and Meyer (1983) subsequently demonstrated that that a linear speed-accuracy trade-off function of the type described by Schmidt et al. (1979) could be obtained only when movement time was constrained, but not when target width was constrained.

In assessing why time constrained single aiming movements and target constrained reciprocal tapping tasks do not conform to the same speed-accuracy trade-off functions, it is important to evaluate the resource compositions of the two types of task. In reciprocal tapping, emphasis is placed on successful acquisition of targets with visual feedback information regarding displacement errors being crucial to successful performance. In the single aiming task, the presentation of only a single target allows the subject to fixate the target without incurring any loss due to the presence of a second target. The true constraint of the single aiming task described by Schmidt et al. (1979) is temporal, with subjects being

required to produce movements in prescribed times. This is different from the reciprocal tapping task, in which the subject is constrained by movement accuracy.

When comparing time constrained single aiming tasks and target constrained reciprocal tapping it is often assumed that movement conditions which have the same nominal difficulty in terms of information, will have the same functional difficulties. That is, they will appear to be equally difficult to the subject. In order to accurately specify workload in a task, and to assess the effects of task manipulation on performance, it is necessary to understand the dimensions of resources being tapped by a particular task. Various movement constraints are predicted to differ in their resource demands and these differences are reflected in a change in the observed speed and accuracy of the aimed movement. Hence, time constrained single aiming movements and accuracy constrained reciprocal tapping tasks, while being of equal nominal difficulty, may display different performance characteristics. These predictions were tested in Experiment 3.

In the following experiment subjects were required to perform single aiming movements under three conditions. In Condition 1 the subject was required to perform a single, rapid aiming movement to a straight line target in a given movement time determined by the experimenter. Subjects were required to estimate the movement time and were given quantitative feedback indicating the timing accuracy of their performance. The variability of movement extent, (W(e)), for movements produced in the required time by subjects in this condition was calculated. W(e) was taken as plus or minus two standard deviations from the mean of the distribution of shots (Welford, 1960). A target was constructed of this width which was separated from the start point by a distance equal to the constant error of movement extent, the mean amplitude, obtained in Condition 1. The same subjects were required in Condition 2 to produce single rapid aiming movements to this target as fast as possible without error. In Condition 3, subjects again produced single rapid aiming movements to a straight line target. However, in this condition the movement time was constrained by means of an auditory metronome which signalled the start and end of the movement time period by auditory pulses. The same movement times were employed in this

condition as in Condition 1.

These movement conditions were established for the following reasons. Conditions 1 and 2 required the subject to perform rapid single aiming movements. The independent variables in the two conditons were, however, different. In Condition 1 the independent variables were amplitude and movement time while in Condition 2 they were amplitude and target width. Furthermore, the constraint on accuracy imposed in Condition 2 was equal to the variability actually produced in Condition 1. A comparison of transmitted information in these two conditions allowed for a test of the nominal eqivalence or the reciprocity detailed earlier.

If reciprocity does not hold, then *it must be assumed that the constraints of accuracy and the constraints of time differed in the demand* they placed on the system in the production of aimed movements. If the demand of the task lies in part, in the specification of temporal aspects of the movement, then in Condition 3 this demand should be reduced because the subject is no longer required to estimate movement time.

METHOD

Subjects

Nine male subjects, students at the University of Alberta, ranging in age from 21 to 27 years, volunteered for the experiment. All subjects wrote with their right hands.

Apparatus and Task

Three amplitudes of movement were selected, 5, 10, and 20 cm. Single line targets were drawn on letter size 28 cm by 21 cm paper. A short line, 15 cm in length was positioned to the right of the sheet to act as the start line. A second parallel line was positioned to the left of this line separated from it by a given amplitude of either 5, 10, or 20 cm. This line acted as the target. Target sheets for each amplitude were reproduced using a Cannon 80 photocopier.

A stylus, 6 cm in length, was constructed by screwing a sharpened metal pointer into the neck of a momentary contact, normally open, DPST switch. The switch was connected to the external event channel of a PDP 11/10 digital laboratory computer. The computer was programmed such that the programmable clock of the computer started when the stylus was lifted and stopped when the stylus was pressed, recording the time elapsed between the events. Hence the movement times for single, self-initiated aiming movements could be measured and stored for later analysis.

In all conditions, the subjects were seated such that the mid-line of the body was aligned with the center of the target, with the target sheet fixed to a table directly in front of the subject. The subjects held the stylus in a pen grip fashion in their right hands, and the wires connecting the stylus to the computer were secured to the subject's arm by velcro straps.

Testing took place over two days with Condition 1 being tested on the first day. In Condition 1 the subject's task was to produce a single rapid aiming movement of given amplitude (specified by the target line) in a specified movement time. The order of testing for movement amplitude was determined randomly and was fixed across all subjects. The order of testing was 10, 20 and finally 5 cm movements. Three movement times were selected, 160, 200, and 240 msec. 160 msec movement times were considered to be fast (i.e. < a simple reaction time), while 240 msec movements were considered slow (i.e. > a simple reaction time). Subjects were required to produce 20 movements at each movement time, and under each amplitude of movement. A movement was considered successful if it fell within plus or minus 5% of the prescribed movement time. The movements were self initiated by the subjects. Following each trial, the computer was programmed to return the movement time for the produced movement, allowing the experimenter to give quantitative feedback to the subject regarding the success of the movement. The experimenter would inform the subject that movements had been successfully completed in the required time, or that they were fast or slow by a given amount. Displacement error for movements which fell within the plus or minus 5% bandwith was measured and used to determine effective target width. Subjects

continued to produce movements until 20 successful movements had been achieved.

Effective target widths for each amplitude, movement time combination were calculated. Effective target width was taken as plus or minus 2 standard deviations of the distribution around the mean displacement. The 9 target widths thus obtained were used to construct targets. Each target was separated from its start point by an amplitude equal to the constant error, or mean amplitude, obtained in Condition 1. These target width, amplitude combinations became the targets for Condition 2.

On day two, subjects were tested in Conditions 2 and 3. The testing method was the same as Condition 1 with the following modifications. In Condition 2 the subject was instructed to produce single rapid aiming movements to each of the presented targets. They were instructed to move as rapidly as possible without missing the target. They were instructed that they would receive 9 blocks of 20 trials, employing a variety of amplitudes and target widths. They were not informed that these amplitudes and target widths represented the data collected on the previous days testing, nor were they given feedback on their movement times. The order of presentation of amplitude and target combinations was the same as that employed in Condition 1.

In Condition 3 subjects were required to repeat Condition 1. However, in this case, movements to the target were paced by means of audible clicks from a Hunter Klock-Kounter Type 1000. Subjects were required to perform 20 trials under each amplitude, movement time combination. The order of testing was identical to that of Condition 1. Series of audible clicks were produced by the clock-counter with the interval between the onset of the first click and the onset of the second click being set to the required movement time. Click pairs were separated by an interval of one second. Subjects were instructed to initiate movements when they were prepared. Several click pairs were sampled by the subject before movements were produced, indicating that the subjects were monitoring the inter-click interval.

Movement time and effective target width were the dependent variables measured in all conditions. Because movement time was constrained in Condition 1 and target width was constrained in Condition 2, a third composite measure was calculated to reflect the

information transmitted in each condition. The Index of Performance, I(p), as detailed by Fitts (1954) was also calculated for each amplitude/time combination in each condition. I(p) is defined as:

$$I(p) = 1/t \log 2\ 2A/W$$

where:

t = movement time

A = Amplitude of movement, and

W(e) = Effective target width

I(p) represents the processing rate, channel capacity expressed in bits per unit time.

Design

The nine subjects were tested under all conditions and all movement time/amplitude combinations. The movement time, the effective target width (W(e)) and the index of performance (I(p)) data were analysed using a three way repeated measures factorial analysis of variance. The levels of the three factors were: 3 (movement condition) X 3 (amplitude) X 3 (movement time).

RESULTS AND DISCUSSION

Figure 24 shows mean index of performance as a function of treatment condition and amplitude of movement averaged across movement time. An analysis of variance performed on index of performance data resulted in significant main effects for amplitude, $F(2,16) = 4.81$, $p<.05$; treatment condition, $F(2,16) = 7.12$, $p<.01$; and movement time, $F(2,16) = 4.42$, $p<.05$. Information transmitted was significantly greater in the target constrained movements than in the time constrained movements. The low transmission rates for the paced movements suggested that the monitoring of the click pairs required resources to a greater degree than in Conditions 1 and 2 and resulted in decreased performance.

The main effects of amplitude and movement time are similar to those reported by Fitts (1954). Fitts reported that movements of 1 and 2 (2.54 and 5.08 cm) inches were

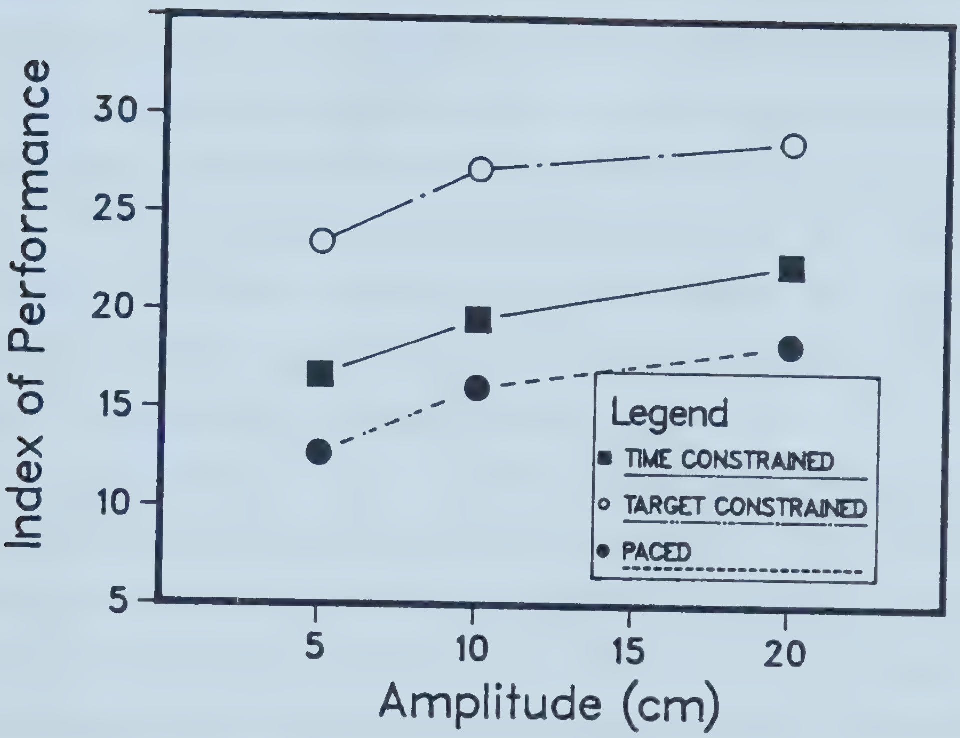

Figure 24. Mean index of performance as a function of Treatment Condition and amplitude averaged across time constraints.

consistently less efficient than movements of 4 and 8 inches (approximately 10 and 20 cm), a finding supported by the results of this third experiment. This experiment also demonstrated that slower movements were less efficient than rapid movements. The cause may be attributed to a change in control strategy from programmed control to feedback mediated control at or around the 4 Hz frequency. Fitts (1954) reported that in reciprocal tasks such a breakdown in performance at the 2 - 3 Hz frequency range. Newell and Wallace (1983) similarly reported that visual feedback information was used in rapid aiming movements only when movement time exceeded 200 msec, and then its use was not consistently observed.

Results of the current experiment appear to be contrary to the assumption of reciprocity. The assignment of independent variables appears to have a major effect on the observed information transmission rate of the human motor system and susequently on the speed-accuracy trade-off relationship observed.

An analysis of variance performed on the effective target width data revealed significant main effects for amplitude of movement, $F(2,16) = 6.28$, $p < .01$; and movement time, $F(2,16) = 4.93$, $p < .05$. No other main effect or interaction was significant. Mean effective target widths are displayed in Figure 26 as a function of treatment condition and amplitude. Increases in the effective target width with amplitude of movement and speed of movement would be anticipated. However, the W(e) was not affected by the manner of movement constraint. That is, movements produced under time constraints, target constaints or movements which were self paced, were all performed with equal accuracy.

The observed changes in I(p) can be attributed directly to changes in movement time. Figure 25 shows movement time as a function of treatment condition for each amplitude of movement averaged across time constraints. An analysis of variance performed on the movement time data resulted in a significant main effect for treatment condition, $F(2,16) = 7.44$, $p < .01$. No other main effect or interaction was significant. Target constrained movements were performed more rapidly than time constrained movements which were themselves faster than the paced movements. This finding demonstrated that the movements constrained by target width could be performed more rapidly, <u>but with equal accuracy</u>, to

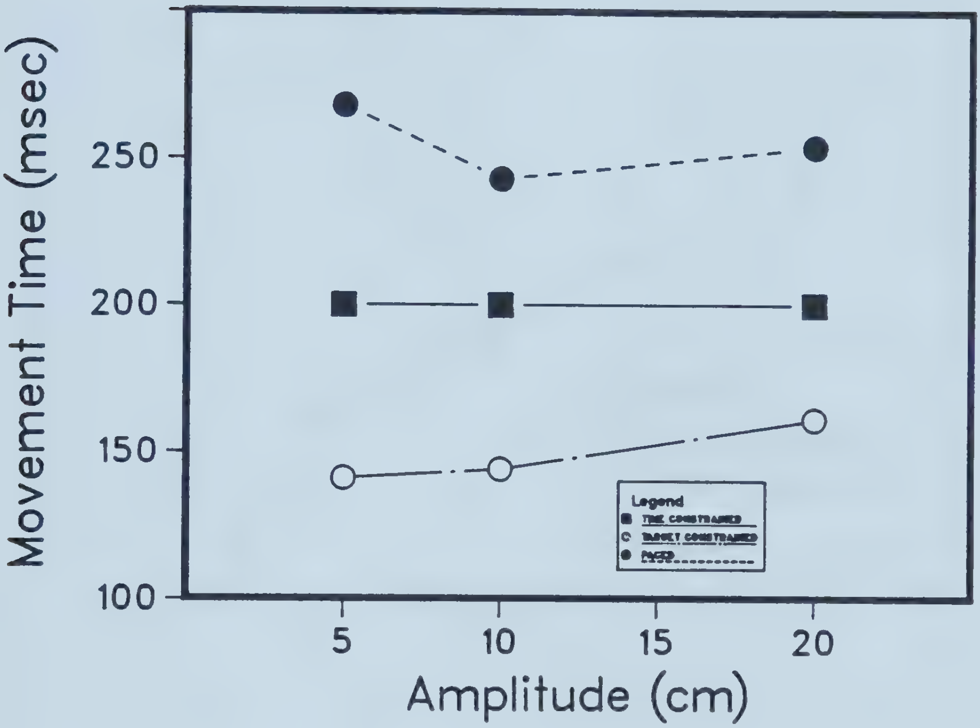

Figure 25. Mean movement time (msec) as a function of treatment condition and amplitude averaged across time constraints.

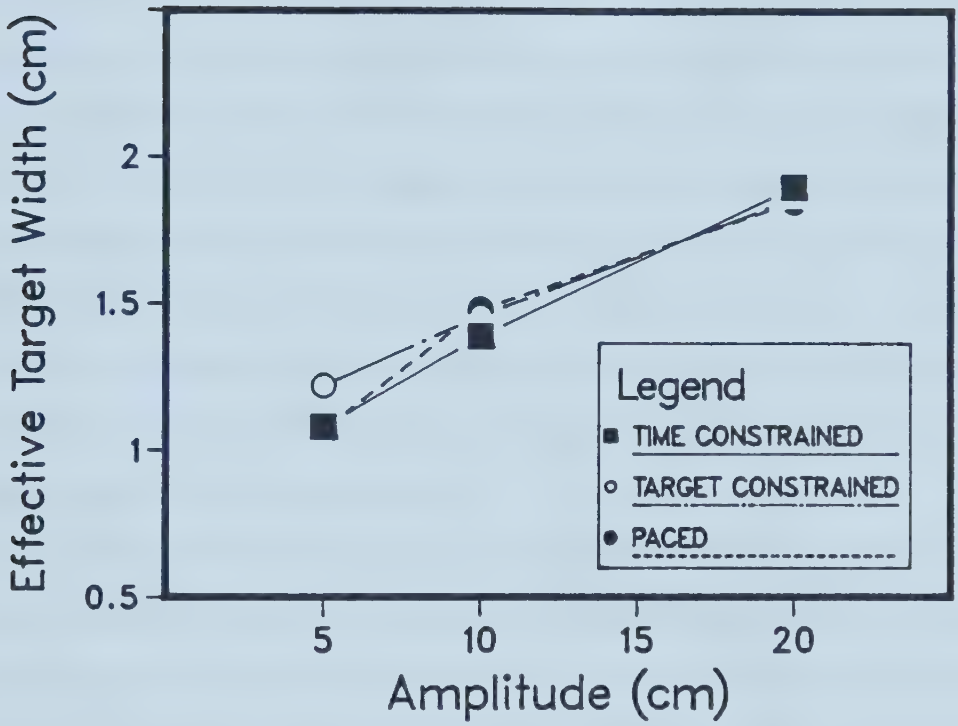

Figure 26. Mean Effective target width (cm) as a function of treatment condition and amplitude averaged across time constraints.

movements which are constrained by time or pacing. These findings would not be predicted by the formulations of Fitts (1954) or Schmidt et al. (1979).

The results of this third experiment suggest that indices such as Fitts' Index of Difficulty are not sufficient indicators of resource demands or of task composition and do not therefore, allow for adequate prediction of performance. Indices which reflect resource composition of tasks would lead to more accurate predictions of performance in aiming tasks and to a better understanding of the phenomenon of speed-accuracy trade-off.

Experiments One and Two demonstrated clearly that in given situations, movements of a fixed amplitude could be speeded without loss of accuracy. These findings did not fit with the expectations of the speed-accuracy trade-off phenomenon and pointed towards a more complex relationship between speed and accuracy of movement. The observed speed and accuracy of movement seems to depend upon the resource composition of the required movement task. As well, the assignment of independent variables is critical in establishing the resource composition of an aiming task.

Wickens (1980) has argued that resources may be defined by a three dimensional metric consisting of stages of processing (perceptual-central versus response); codes of perceptual and central processing (verbal versus spatial) and modalities of input (visual versus auditory) and response. This view contrasts with Kahneman's (1973) model which assumes an undifferentiated pool of resources with competition for resources occuring between satellite structures. Assuming that subjects exhibit complimentarity (see Navon and Gopher, 1979), that is, they devote all resources to the task, it could be argued that in Experiment One resource limitations on one target were reduced when the width of the paired target was increased. This effect only continued until the width of the paired target entered its data limited region (in this case approximately 4 cm) at which time no further resources could be made available for acquisition of the fixed target. In Experiment 2 evidence was presented which suggested that the resource limitations were related to the availability of visual feedback information to the subject and the acquisition of this information by visual monitoring. Crossman and Goodeve (1963) and later Wallace and Newell (1983) demonstrated that rapid

movements (movements which show no evidence of within movement correction) could be accurate to approximately 90% of the required movement amplitude. These are similar findings to those of Woodworth (1899) and appear to indicate the transition point at which aiming movements move from resource limitation to data limitation.

Experiment 3 demonstrated the importance of task structure. In Condition 1 subjects were required to produce aiming movements to a narrow target (a thin straight line) in prescribed movement times. Line targets represent demanding aiming tasks where the accuracy requirements are maximal. In Condition 1 this demanding task was coupled with a fairly difficult temporal estimation task. In Condition 2 the accuracy requirements of the task were reduced by provision of wider targets and temporal estimation was completely eliminated since subjects were not constrained by movement time. In Condition 3 the highly demanding accuracy task was coupled with a temporal estimation task, and the difficulty of this condition was further increased by an auditory monitoring task. It does not appear surprising, therefore, that performance in Condition 2 was superior to Condition 1, and both of these were superior to Condition 3.

The interesting point was that performance differences in the three conditions were related to movement time and not movement accuracy. The implication is that accuracy is insensitive to changes in resource composition caused by altering the temporal requirements of the task. This might speak in favor of the multiple resource approach advocated by Norman and Bobrow (1975); Navon and Gopher (1979) and Wickens (1984). It is further supported by the work of Bizzi and Polit (1979) who have shown evidence for separate mechanisms for the control of accuracy of movement and speed of movement, and of Wright and Meyer (1983) who demonstrated that the linear speed-accuracy trade-off function described by Schmidt et al. (1979) could only be obtained when movement time was constrained but not when accuracy was the constrained variable.

A more complete understanding of the demands associated with particular response variables is essential if a clear picture of the speed-accuracy trade-off phenomenon is to be gained.

5. EXPERIMENT FOUR

Experiments which manipulate the required accuracy or timing of a movement with the intention of effecting a change in performance outcome assume that such manipulations affect the workload associated with performance of the task. Early treatments of the concept of operator workload such as those of Rolfe (1971) viewed the workload of a task as being inversely related to the percentage of resources or capacity not devoted to the performance of a primary task. Increased interest in the concept of operator workload has led to the development of a number of proposed measures of workload, with Wierwille et al. having enumerated some 28 different techniques (Wierwille, Williges and Schiflett, 1979; Wierwille and Williges, 1980). Wickens (1984) reports, however, that there is no clear concensus of what workload is and whether the proposed measures tap the same or different constructs.

Primary task manipulations are most commonly seen in studies dealing with the phenomenon of speed-accuracy trade-off. The manipulation of primary task parameters, for example, the changing of required accuracy, or changes in the speed of movement in an aiming task, are made with the intention of increasing or decreasing workload. It is usually assumed in such cases that workload is sensitive to the parameter being manipulated. The effect of a manipulation on workload is dependent however, on the subject's response to the manipulation. In many cases, subjects may choose to ignore increased demand brought about by parameter manipulation, and maintain performance at a previous level. It is unlikely therefore, that such a manipulation can lead to increased operator load. Furthermore, certain parameter manipulations may not result in resource limits being reached with the result that performance decrements will not be observed. This leads to the false assumption that workload has not increased. As was the case in Experiments One, Two and Three, in order to specify accurately the workload effects of primary task manipulations it is important that the nature and magnitude of the manipulation and of the change in primary task performance, be described.

As was noted in Experiment Two, in order to accurately specify the workload imposed by a task or task manipulation the dimensions of resources affected by the task must be identified. For example, movements constrained by amplitude and target width do not necessarily tap the same resources as those movements constrained by movement time and amplitude, leading to the differences in observed performance. It is also necessary to identify the primary task workload margin (i.e. the magnitude of change in the primary task parameters which is necessary to deplete resources required for performance of the task to the extent that performance changes are observed). This is the workload margin because it provides an index of how much additional demand a resource can bear before performance becomes unsatisfactory.

In many experiments dealing with the phenomenon of speed-accuracy trade-off, the variables are manipulated in order to increase the workload by a factor of two (i.e. by increasing amplitude of movement by a factor of two while target width remains constant, or by decreasing target width by a factor of two while amplitude remains unchanged). Few attempts have been made to investigate performance changes when the workloads are varied by small increments. Bailey and Presgrave (1958) presented average velocities of movements to a target for 20 amplitudes of movement, ranging from 1 to 30 cm, and 5 target tolerances. The results generally conformed to Fitts Law, however details involving procedures were somewhat limited. One drawback of the investigation was that in increasing amplitude of movement and measuring resultant velocity of movement, displacement and timing errors are confounded (Hancock and Newell, 1985).

Experiment Four examined the workload margin in performance of reciprocal tapping tasks. In the current experiment only a single amplitude of movement was selected (15 cm), in order to avoid problems associated with amplitude manipulation. Twenty five target pairs were constructed, increasing in width from 8 mm to 32 mm giving a range of movement difficulty from the most difficult condition at 5.195 bits, to the least difficult at 3.2 bits. Difficulty increments ranged from 0.17 bits between the 8 and 9 mm targets, to 0.04 bits between the 31 and 32 mm targets.

METHOD

Subjects

Ten subjects, students in the faculty of Physical Education and Recreation at the University of Alberta, ranging in age from 21 to 27 years, volunteered for the experiment. All subjects wrote with their right hands.

Apparatus and Task

Twenty five sets of target pairs, which consisted of two circular targets separated by an amplitude of 15 cm, were constructed on 50% rag paper. The smallest target pair consisted of two equal sized targets of 8 mm diameter. Subsequent target pairs were produced by increasing the diameter of both targets by 1 mm steps until the 25th and largest target pair was obtained consisting of two equally sized targets of 32 mm diameter. The index of difficulty described by the target combinations ranged from 5.195 bits for the smallest pair, to 3.2 bits for the largest pair.

A PDP 11/10 digital computer was employed to control the experiment and to collect data from a Summergraphics supergrid clear glass digitizing tablet. Targets were mounted on the underside of the digitizing tablet and were clearly visible through the glass. A pen type stylus was connected to the digitizing tablet and allowed for the collection of positional data which was stored by the computer and used for later analysis.

At the beginning of each trial the subject was required to position the stylus on the left hand target of the target pair. Following an auditory signal by the computer the subject was required to move alternately between the targets as fast and as accurately as possible without taking the stylus from the glass. After a 20 second bout of reciprocal movement during which the computer sampled and stored digital information at the rate of 100 samples per second, a second tone was issued indicating the end of the trial. Stored digital information

was later used to calculate movement extent, movement time, and variability of movement endpoint (W(e)) for each target in the target pair.

The 25 target pairs were presented to the subject in random order, as determined prior to testing by the generation of random numbers using the PDP 11/10 computer. This order of presentation was repeated 5 times, giving a total of 125 tapping bouts. All subjects recieved the same order of presentation of targets.

The subject was seated such that the midline of the body coincided with a point midway between the targets in the target pair. The subject was instructed to hold the stylus in a pen grip fashion and to begin each movement bout with the stylus positioned on the left hand of the two targets.

Following each 20 second movement bout the subject was allowed to rest while the Experimenter changed the target pair. Following presentation of each 25 target pairs, representing presentation of one complete set of targets, the subject was asked to evaluate the number of different target combinations that had been presented.

RESULTS AND DISCUSSION

Figure 27 shows mean variable error as a function of direction of movement and target width. An analysis of variance performed on error data resulted in a significant main effect for target size being identified $F(24,240) = 41.18$, $p < .001$. No other main effect or interaction was significant. As would be expected, errors increased on both the left and right targets as target width increased, with the rate of increase leveling as targets increase in width. This plateau would be expected as movement difficulties approached 4 bits, when, according to Wallace and Newell (1983) movements can be performed without the need for feedback corrections.

Figure 28 shows mean movement time as a function of direction of movement and target width. An analysis of variance performed on movement time data resulted in a significant main effect being identified for target width $F(24,240) = 54.26$, $p < .001$. No

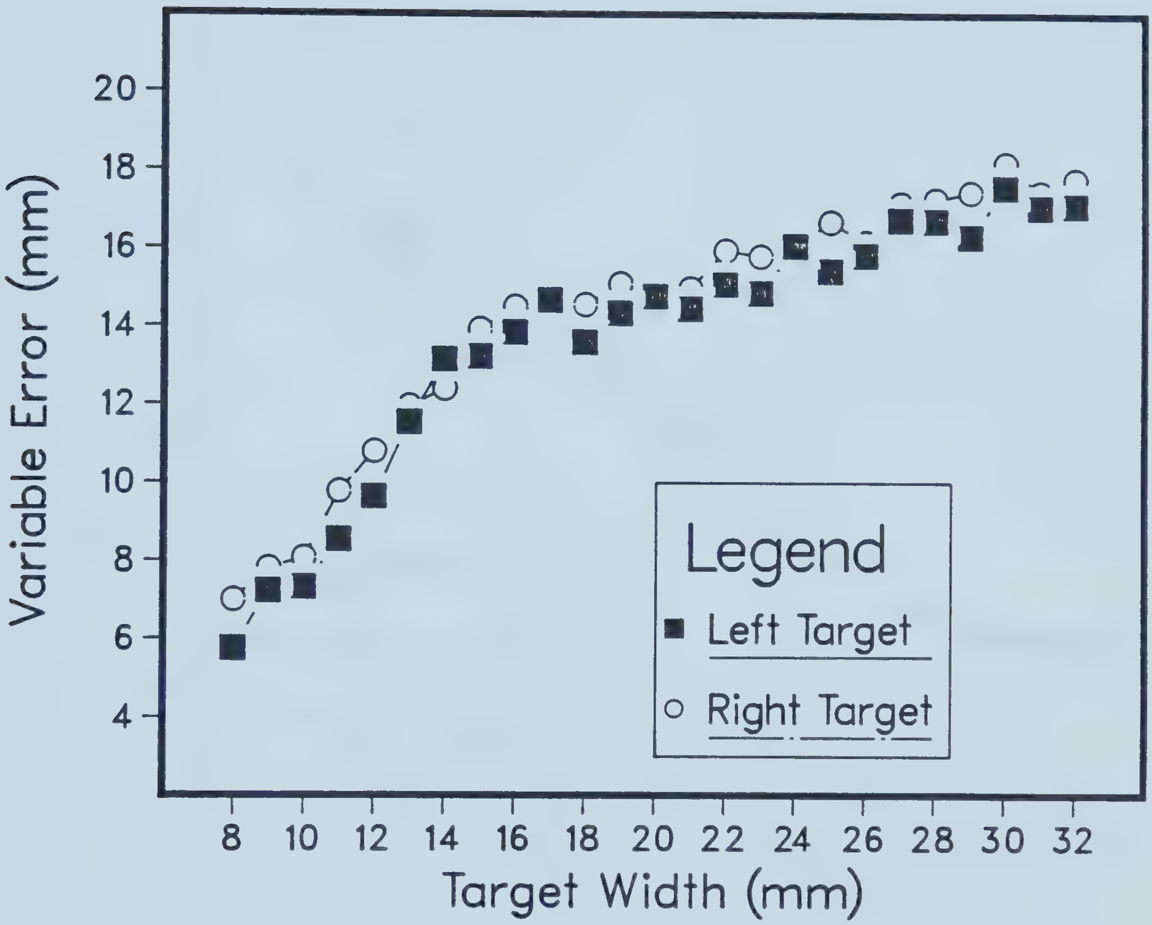

Figure 27. Mean variable error (mm) as a function of direction of movement and target width.

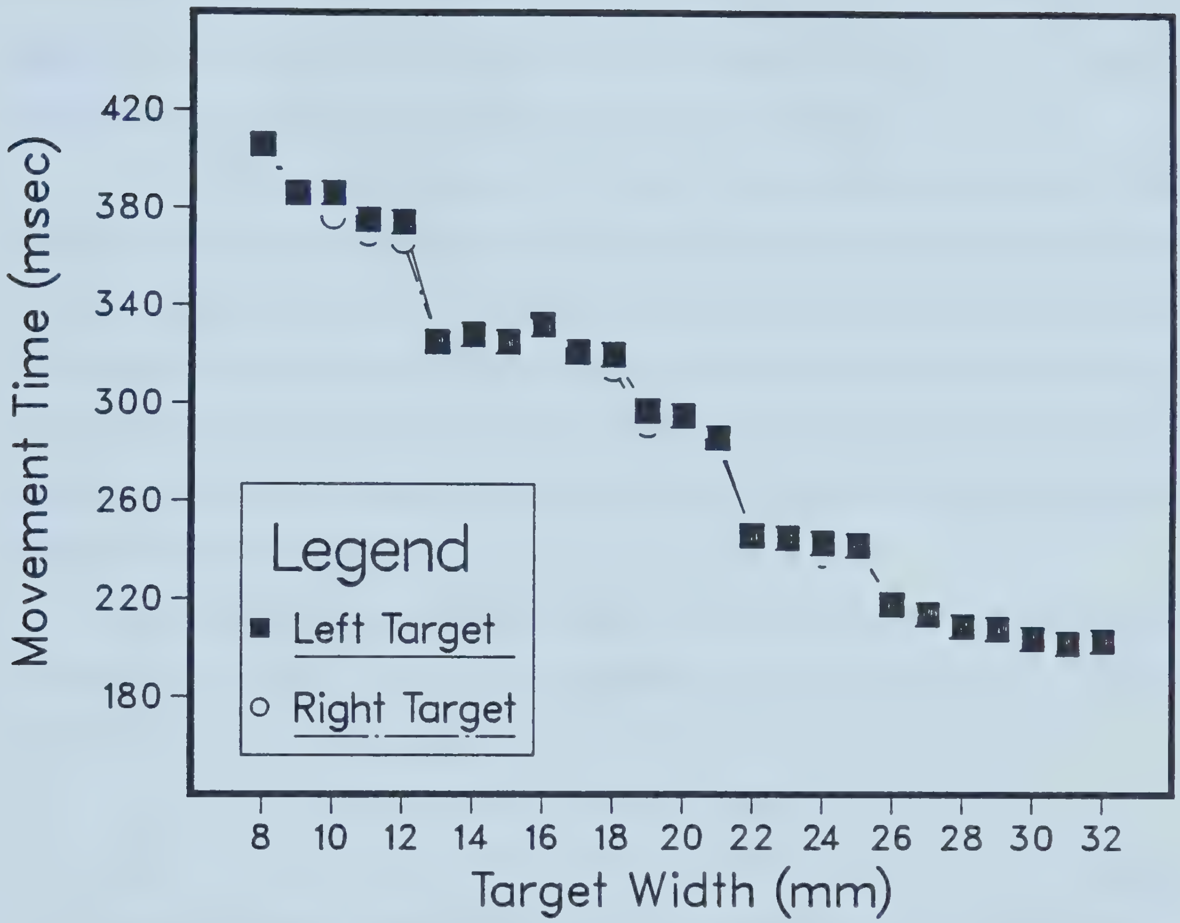

Figure 28. Mean movement time as a function of direction of movement and target width.

other main effect or interaction was significant. An interesting feature of the movement time data is the apparent step-wise decrease in movement time with increases in target width. Tests on the simple main effects indicated the least significant difference between consecutive means to be 22 msec. On this basis, five distinct clusters of movement times were identified. This approximates the number of unique target widths reported by subjects, with all subjects having reported that only 5 different target widths had been presented.

Based on the step-wise decrease in movement time with increasing target width, workload margin was estimated as the mean information change required to produce a change in movement time. Workload margin was estimated to be approximately 0.4 bits. The increase in target width required to increase the movement difficulty by approximately 0.4 bits would be in the order of 30% of the original target width. In other words the targets would be thought to be from the same category as long as they did not differ by more than 30%, given the present order of presentation.

The results of this experiment are interesting for several reasons. Fitts' Law states that movement time (MT) is related to the nominal movement amplitude (A) and terminal accuracy (W) in terms of the model,

$$MT = a + b(ID) \text{ where } ID = \log2(2A/W)$$

The inverse of b (1/b), in the above equation is generally regarded as the generated information rate expressed in bits/unit time. Fitts' Law suggests that the information rate is fixed with respect to movement time. Kvalseth (1980) states that while accommodating a variety of data, Fitts' Law is an invalid information theoretic measure, and the fixed information rate implied by the equation is of doubtful validity. Fitts' original data give values of 1/b ranging from 9.5 to 11.6 bits/second. The power function derived by Kvalseth predicts that 1/b is an exponentially decreasing function of ID and is therefore, better able to account for the observed changes in generated information with ID.

Data from this fourth experiment would suggest that the relationship between ID and movement time is not a power function since movement time does not change in a smooth manner, but rather, in a step-wise fashion. Ross and DiLollo (1970) demonstrated that power

laws may fail to accommodate magnitude estimates of lifted weights. Functions relating estimated weight to presented weight showed a series of steps or inflections which were inconsistent with a uniformly concave or convex power function. The step type function occurred in a variety of experiments which varied subjects, the range of comparison weights, the magnitude of the standard weight, and the position of the standard weight with respect to the stimulus range.

Similar effects to those reported by Ross and DiLollo are evident in the current experiment. Slope and intercept parameters for the function relating ID and MT were obtained using linear regression analysis. For movements to the left Fitts' Law accounted for 89% of variance (MT = -236 + 151 ID) while for movements to the right it accounted for 85% of variance (MT = -187 + 135 ID) even though the function relating ID and MT was not uniform. While giving a good overall fit to the data, Fitts' Law is misleading as to the exact relationship between difficulty and movement time.

In the current experiment only a single order of target presentation was used. A more complete understanding of workload margins would be obtained if factors such as range of target width, size of the first presented target, and the position of the first presented target with respect to the stimulus range, were manipulated (see Ross and DiLollo, 1970; and Norwich, 1981, for a detailed argument). Furthermore, estimates of the subject's ability to make categorical judgements of target size in the absence of movement would shed light on the locus of the categorical effect. That is to say, whether the effect is perceptual, dependent upon the subject's ability to discriminate targets, or whether it is response based, dependent upon the subject's ability to discriminate responses as being different.

It is of interest that the number of categories reported by subjects falls within the range of Miller's magical number of 7 plus or minus 2 (Miller, 1956). Norwich (1981) reports that the ability to discriminate between nearly identical stimuli is vastly superior to the ability to make absolute judgements. When subjects are required to identify stimuli as belonging to a particular category they are limited to approximately five categories, even when there is no difficulty in discriminating between categories. In contrast, however, when the ability to

discriminate between nearly identical stimuli is tested the number of distinctions that can be made is relatively large (i.e. over 100 differences in intensity of tone (Norwich, 1981)).

Several theories have been presented to account for this limitation in categorical judgement. Siegel (1972), for example, has suggested that limitations can be due to limitations in sensory capacity in which sensory modalities limit the transmission of information, or due to memory capacity limitations. Whatever the source of the limitation, it would appear that the workload margin is related to the subject's ability to make categorical judgements. In the current experiment subjects identify only five categories of target width. These categories appear to be the basis upon which subjects determine the speed of the movement to be produced. When the subject determines two targets to belong to the same category, then movement times are equivalent. Displacement errors are, however, related to the size of the aimed for target, which is consistent with the fact that feedback information is available to the subject regarding the accuracy of performance. No such information is available regarding the speed of movement, however, and this gives rise to the fact that transmitted information decreases for larger targets within a category.

The current experiment demonstrates the importance of the workload margin in understanding performance in aiming tasks. In this fourth experiment all decrements in the demand of the task brought about by increasing the size of the aimed for target were not perceived by the subject as changes, due to a limitation in the subject's ability to make categorical judgements. The result is that while a change in performance might be predicted on the basis of Fitts' Law, no change may actually occur.

Revisions to the current experimental methodology may overcome many of the limitations evident in the current approach. Manipulating the range of the presented targets, changing the size of the first presented target and the subsequent orders of presentation, and manipulating the position of the first presented target with respect to the stimulus range, would provide information regarding the nature of the categorical effect. Estimates of the subject's categorical judgement of target size based upon psychophysical methods would help in indicating the locus of the categorical effect as being either perceptual or motor output.

6. EXPERIMENT FIVE

Researchers have assumed in their examination of the phenomenon of speed-accuracy trade-off that task load was related solely to the physical constraints imposed on the operator by the task (Fitts, 1954; Schmidt et al., 1979). Task load is commonly expressed in informational terms, with the difficulty of any given movement being dependent upon required accuracy, movement amplitude, and movement latency. Results of Experiment 3 challenged this common assumption and demonstrated that movements of equal nominal difficulty in terms of information produce quite different functional outputs from the operator. How the movement is constrained, whether by accuracy and movement amplitude or amplitude and movement time, is critical in determining the nature of the speed-accuracy trade-off function observed.

Linear speed-accuracy trade-off functions such as those of Fitts (1954), Welford (1965), Kvalseth (1979,1980), Schmidt et al. (1979), and Meyer, Smith and Wright (1982) assumed that linear changes in task demands expressed in information terms resulted in linear changes in output on the part of the subject. Experiment 4 demonstrated, however, the importance of assessing workload margin in determining performance output. While the task provided 25 unique workloads, subjects perceived only 5 and their output in terms of movement time reflected this limited perception of movement categories.

Navon and Gopher (1980) suggested that performance could be measured in terms of accuracy, latency, and rate. They postulated that accuracy was directly related to the actual output of the system divided by the task load. In informational terms, if the system can not operate beyond 3 bits and task load is 4 bits then either accuracy suffers, or processing duration is limited. In such cases two outcomes are possible. Either, the assignment is partly completed, the result being an inaccurate movement; or the output will lead to a correct response with a particular probability. This probability is related to the processing duration such that:

Probability of correct performance = Processing duration X output rate/load.

In situations when the duration is not limited then the latency to criterion is given by:

$$\text{Latency} = c + \text{load/Output rate},$$

where c is some constant period representing the contribution of factors that are unrelated to processing done with the resources in question.

In order to measure performance therefore, it is essential to understand the factors which combine to determine task load. Both Fitts and Schmidt et al. assumed that these factors involved the physical parameters of the task and that observed performance would be related solely to those parameters. Navon and Gopher (1979) and Norman and Bobrow (1975) have suggested that performance is related not only to task demand, but also to the policy of resource allocation adopted by the subjects in given task situations. This allocation policy is thought to be critically influenced by the subjective utility adopted by the subjects. Norman and Bobrow proposed that all levels of performance falling on a single indifference curve are considered of equal utility to subjects. Friedman and Polson (1981) made an interesting division between actual task difficulty and perceived task difficulty. They suggested that:

> "the dual task situations were either in fact more difficult and demanded more resources or were perceived as being potentially more difficult, so that the utility for allocating resources was increased." (p. 1044).

The fact that tasks can be perceived as being more difficult than the task parameters would suggest is an important observation. Load, in the sense the term is used by Navon and Gopher (1980), can, therefore, be made up of perceptual as well as physical components. This suggests that the utility for allocating resources can be influenced not only by actual task difficulty but also by the perception of task difficulty.

If, as Experiments 1 and 2 would suggest, subjects utilize all available resources during performance, such that in all target combinations the resources devoted to the fixed target (Rft) plus those allocated to the variable target (Rvt) equal the total limit of resources (Rlimit) (i.e. Rft + Rvt = Rlimit), then an increase in difficulty brought about by a change in perception of task difficulty should result in observeable changes in performance.

Experiment 5 tested the idea that perceived task difficulty can significantly affect resource allocation policies adopted by subjects in a reciprocal tapping task and subsequently influence performance outcome.

To test the hypothesis that perception of task difficulty can influence performance outcome a task was devised which influenced the subjects' perception of task difficulty while, at the same time, maintaining actual task difficulty, as measured in information terms, at a constant level. This was achieved by utilizing a perceptual phenomenon known as the Ebbinghaus illusion. In Condition One, two target circles 1.5 cm in diameter were separated by an amplitude of 8 cm. No contextual information was presented. In Condition Two, the same target circles, again separated by an amplitude of 8 cm, were embedded in surrounds which consisted of six equally spaced circles of diameter .75 cm. In Condition Three, the right hand of the two targets was surrounded by .75 cm circles as in Condition Two, while the left was surrounded by six equally spaced circles of 3 cm diameter. The effect in this condition is to produce an optical illusion in which the target embedded in the surround of larger circles appears smaller than its partner which is embedded in small circles.

In order to demonstrate the presence of the illusory effect, subjects were presented with the illusory target pair and asked to identify the apparently larger and smaller circles. They were not informed that the targets were the same size. Subjects were then presented with a table containing 25 circles ranging in increasing diameter from 8 mm to 33 mm and asked to identify the circle corresponding in size to the apparently large target of Condition Three and, similarly, the apparently small target. These targets were then used, separated by an amplitude of 8 cm and without contextual surround, as a control condition.

Comparison of performances in a reciprocal tapping task conducted between the conditions described allowed for the identification of the effects of contextual information per se, and, more importantly, the effect of visual illusion in which the apparent and the actual task difficulties do not coincide.

The following hypotheses were formulated and tested in the current experiment. First, the effects of context per se on performance, as indicated by measures of movement accuracy

and time, would not be significant when both targets appeared in the same context. Second, for the illusory conditions (Conditions 3 and 4) the appearance of the apparently smaller target would cause the subject to direct more resources to that target, with the result that fewer resources would be available for acquisition of the apparently larger target. This would result in performance decrements on the apparently large target which would be evidenced by increased error when compared to the apparently small target. Two control conditions were established. Subjects were required to select from a table of circles, those circles which appeared to be equal in width to the targets presented in the illusory conditions. In Condition 5 the large circle appeared to the subject's right and the small circle to the subject's left. In Condition 6 the position of the circles in Condition 5 was reversed. In these conditions, a pattern of results similar to those expected for Conditions 3 and 4 would be anticipated since the division of resources would be based on real differences in target widths.

METHOD

Subjects

14 male subjects, students in the Faculty of Physical Education and Recreationat the University of Alberta, ranging in age from 20 to 28 years, volunteered for the experiment. All subjects wrote with their right hands.

Apparatus and Task

The apparatus employed in Experiments 1 and 2 was utilized in the current experiment.

Subjects were instructed that they would be required to perform 6 trials, where a trial consisted of 15 seconds of reciprocal movement between two presented targets. Subjects were further instructed that following each 15 second trial, the experimenter would change the

target pair prior to commencement of the next trial.

Prior to the start of the experiment, subjects were shown the Ebbinghaus illusion which was to be used in Conditions 3 and 4. From a table of circles ranging in diameter from 8 mm to 32 mm subjects were required to identify a target which corresponded in size to the apparently smaller target of the illusory pair, and also a circle corresponding in size to the apparently large target. These identified circles were used to construct the target pair to be used in Conditions Five and Six.

In Condition 1, two 1.5 cm targets with no contrasting surround, were separated by an amplitude of 8 cm. In Condition 2, the same 1.5 cm targets, each with a surround of six equally spaced circles of .75 cm diameter, were separated by an amplitude of 8 cm. In Condition 3 the right hand target, again a 1.5 cm target, was surrounded by six equally spaced circles of .75 cm diameter, while the left hand target was embedded in a surround consisting of six equally spaced circles of 3 cm diameter. This created the Ebbinghaus illusion effect, in which the left hand target appeared smaller than the right hand target. Condition 4 consisted of a repeat of the Ebbinghaus illusion of Condition 3, however, the apparently large target appeared to the subject's left, while the apparently small target appeared to the subject's right. Condition Five was constructed using the targets that the subjects had identified as being equivalent to the apparently large and small targets of the Ebbinghaus pair of Conditions 3 and 4. In Condition 5, the large circle appeared to the subject's right, while the small circle appeared to the subject's left. In Condition 6, the position of the targets in Condition 5 was reversed such that the large circle appeared to the subject's left, while the small circle appeared to the subject's right.

The computer was programmed to give warning tones of 1 second duration using the ennunciator in the Summagraphics digitizing tablet. Following an intial tone, the subject was required to place the tip of the stylus in contact with the left hand target of the target pair. Contact between the stylus and the digitizing tablet started the programmeable clock of the computer and after a fixed delay of 3 seconds the computer sounded a second tone which was the subject's signal to begin moving. Subjects were instructed to make the first movement to

the right hand target of the pair, without removing the stylus from the glass, and to subsequently alternate movements between targets. They were instructed to move as fast and accurately as possible. Following the 15 second movement interval, the computer sounded a third tone indicating the end of the trial. At this time the subject rested while the Experimenter changed the target pair. Each of the six conditions was presented to the subject once. The conditions were presented in random order to each subject.

During the movement interval the computer was programmed to sample at a rate of 100 samples per second from the X coordinate of the digitizing tablet. This data was stored by the computer and later used to calculate movement extent and movement time in the left and right directions, and effective target widths for each target in the target pair. The first movement to the right, which contained a reaction time component, was excluded from this analysis.

Design

All subjects performed all conditions of movement. Data was analysed using a two way factorial analysis of variance with repeated measures on both factors. The levels of the two factors were: 6 (context condition) X 2 (direction of movement).

RESULTS AND DISCUSSION

Figure 29 shows mean movement time as a function of the direction of movement and the treatment condition. Analysis of variance performed on movement time data resulted in significant main effects being identified for the variables direction of movement $F(1,13)=6.25$, $p <.01$ and movement condition $F(5,65) = 2.23$, $p < .05$. The direction of movement by treatment condition interaction was not significant. Tests of simple main effects indicated that for all treatment conditions movements to the left were performed significantly faster than movements to the right. The magnitude of the left/right difference in movement

time was in the order of 5 msec. Similar analysis indicated that movements in Condition 1 were significantly faster than in all other conditions, which were not significantly different from each other. It would appear that the presence of any target surround was sufficient to slow movements to that target, whether the surround produced an illusory effect or not. The effect of the illusory conditions is evidenced by the fact that movement times in the illusory conditions 3 and 4 are equivalent to the control conditions 5 and 6. Furthermore, in keeping with the findings in Experiments 1 and 2, the movement times are faster when the apparently small target in the illusory pair appears to the subject's left (Condition 3) compared to when it appears to the subject's right (Condition 4). Similarly, in the control conditions, the movement times are faster when the small target appears to the subject's left (Condition 5) than when it appears to the subject's right (Condition 6).

Figure 30 shows the mean effective target width as a function of the direction of movement and the treatment condition. An analysis of variance performed on the effective target width data resulted in significant main effects being indentified for the variable direction of movement $F(1,13) = 4.29$, $p < .01$. The direction of movement X treatment condition interaction was also significant $F(5,65) = 2.51$, $p < .05$. Tests of the simple main effects for the direction of movement indicated that for conditions 3 and 4 the differences between left and right target errors were significant, but the directions of the differences were opposite. The smallest error was associated with the perceived small target, independent of position (left or right). The magnitude of the difference in errors was greater when the perceived small target appeared to the subject's left. Similarly, for the control conditions, 5 and 6, the differences between left and right errors was significant when the small target appeared to the subject's left (Condition 5) but not when the small target appeared to the subject's right (Condition 6). In Condition 6, however, the direction of difference was as expected, with the small target, which was situated to the subject's right, having smaller error than the large target. This difference was not, however, significant.

The results of the current experiment appear to support the hypotheses suggested by Navon and Gopher (1979), Norman and Bobrow (1875) and Friedman and Polson (1981)

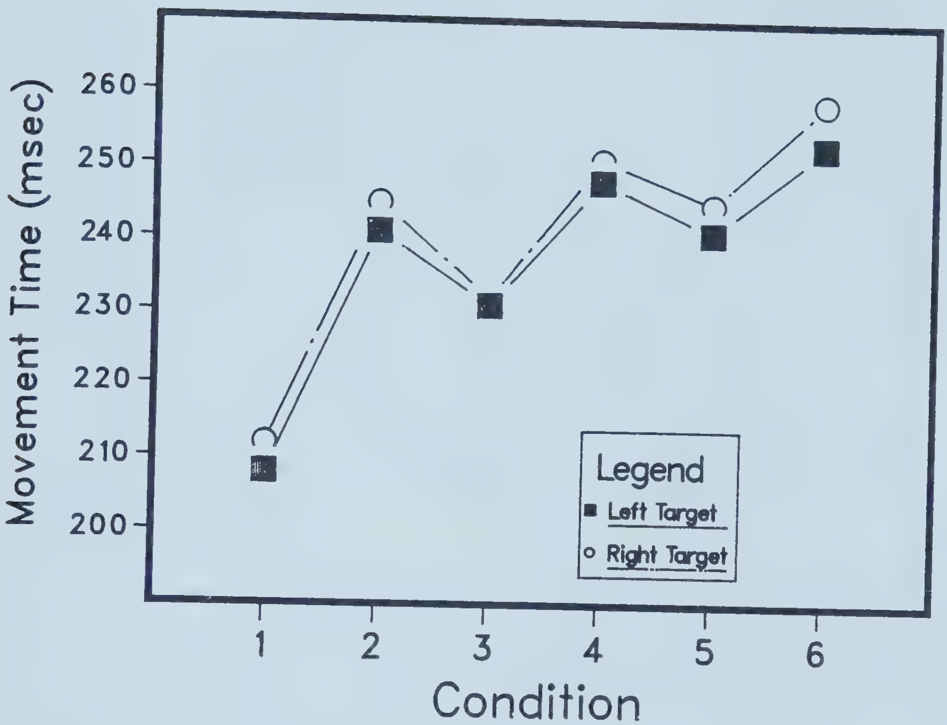

Figure 29. Mean movement time as a function of direction of movement and treatment condition.

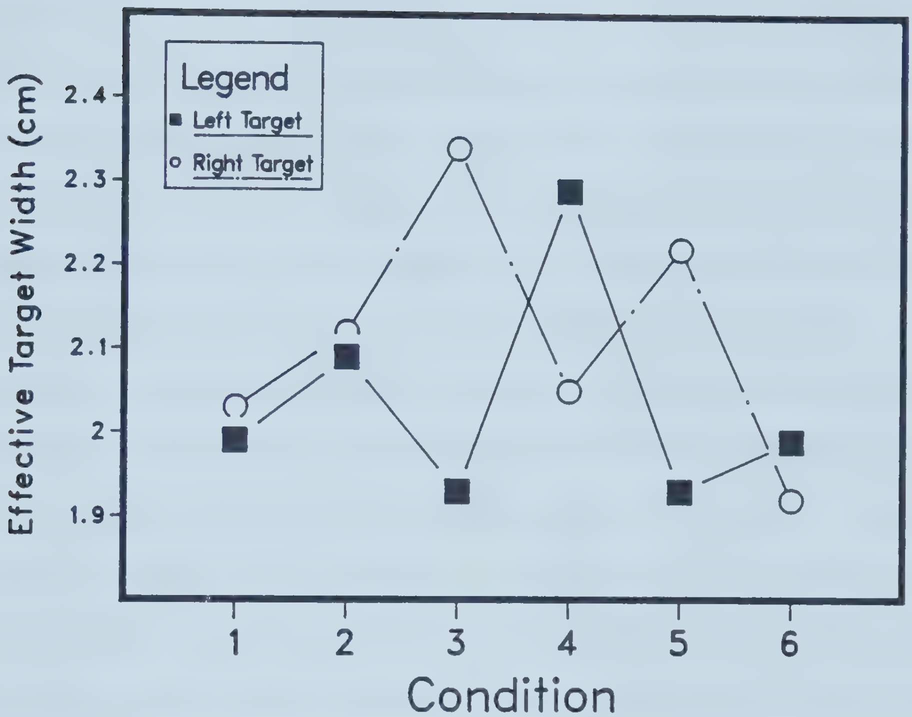

Figure 30. Mean variable error as a function of direction of movement and treatment condition.

that performance is related not only to task demand, but also on the policy of resource allocation adopted by the subject in given task situations. It is apparent that when the subjects perceive there to be a difference in the demands associated with the targets in a target pair, that they devote more resources to the target which is perceived to be the more difficult to acquire. This is evidenced by the fact that in Conditions 3 and 4, the errors on the perceived small target are significantly less than those on the perceived large target. This effect is most evident when the perceived small target appears to the subject's left, but is still significant when it appears to the subject's right. The differences in the magnitude of the effect would be anticipated given the results of Experiments 1 and 2. The same effect is observed in Conditions 5 and 6, where the targets actually did differ in size. The magnitude of the differences is not as great in the control conditions as in the illusory conditions, and this may be the result of differences in the contextual surrounds between the conditions. Howarth and Beggs (1985) suggest that the mere presence of a second target within the subject's visual field is sufficient to cause shifts of eye fixation, with decrements in performance being the result. A comparison of Conditions 1 and 2 shows the effect of embedding targets in contextual surrounds. Although Conditions 1 and 2 have the same nominal difficulty, there is an obvious effect of the surrounding targets in Condition 2 which results in decreased performance. Similarly, when comparing performance in Conditions 3 and 4 with that of Conditions 5 and 6, where no surrounding targets are present, the effect of unequal target sizes is apparent in Conditions 5 and 6 but is not as great as in Conditions 3 and 4 where surround effects are also evident.

Experiment 5 demonstrates that performance can be influenced by subjective perception of task difficulty and that performance is based not only on actual task difficulty as indexed by required accuracy, amplitude and speed of movement, but also by the subject's perception of task difficulty. A stronger case could have been put forward had the frequency of eye fixations and their durations been measured during performance of the task. If demand is reflected by position of the eyes, as suggested in Experiment 2, and decreased errors are associated with increased frequency and duration of eye fixation, then similar patterns of eye

fixations should have been evident between the conditions of Experiment 5 as were evident in Experiment 2. Further experimentation, including estimates of eye fixation, is required in order to evaluate the role of perceived difficulty in determining performance outcome.

7. GENERAL DISCUSSION

The relationship between the speed of movement and its subsequent accuracy has been a focus of experimental research in human performance since Woodworth first examined the question in 1899. In a variety of simple motor tasks, performed with and without the aid of visual monitoring, Woodworth (1899) demonstrated that for rapid, visually guided movements, variable error increased with both the speed and amplitude of movement. The application of information theory to the study of motor function allowed for a more specific measurement of performance capacities (Crossman, 1955; Hick,1952). Fitts (1954) stated that the information capacity of the human motor system is specified by its ability to produce "one class of movement from among several alternative movement classes" (Fitts, 1954, p.381). Further, "The greater the number of alternative classes, the greater is the information capacity of a particular type of response". (p.381). From this, Fitts concluded that since measurable aspects of movement such as amplitude and force are continuous variables, information is limited only by the amount of variability that is characteristic of repeated attempts to produce the same response. The information capacity of the motor system can be assessed therefore, from measures of the variability of responses which are meant to be uniform.

Fitts' theory states that, if the information transmission capacity of the motor system is fixed, and if repetitive movements of average amplitude were 'speeded-up' then each movement could provide less information and, therefore, movement variability would increase by a specified amount. Fitts formulated an index of difficulty which specified the minimum information required for the organization of a movement. In binary notation:

$$ID = \text{Log2 } W/2A \text{ bits per response,}$$

where:

ID = Index of Difficulty,

W = Tolerance range in inches, and

A = Average amplitude.

The results of Fitts' experiments confirmed that movement time varied with task difficulty such that ID was constant over a wide range of amplitudes and tolerances. In other words, movements of different amplitudes, but of equal difficulty in terms of information, are of approximately equal duration. The average time per movement was given by the formula:

$$MT = a + bLog2\ 2A/W$$

where a and b are emprically fitted regression parameters.

In Experiment 1 it was suggested that Fitts' Law had some very specific predictions about the effect of manipulations of task difficulty on performance. Specifically, it was suggested that if the information analogy proposed by Fitts was correct, then any manipulation of task parameters which resulted in a reduction of overall demand on the subject should have resulted in movements which were faster and/or more accurate. Therefore, if one target in a reciprocal tapping task was made wider realtive to its partner then movements to the smaller, fixed target, should have been faster and/or more accurate than they would have been if the same small target had been paired with a target of equal width.

The results obtained in Experiment 1 supported the above expectations. When one target in a target pair increased in size realtive to its partner, which remained fixed, movements to the fixed target became faster and more accurate as the paired target increased in size. Given the relationship between speed and accuracy proposed by Fitts' Law, the observation that movements could be speeded while at the same time becoming more accurate, was a marked departure from the expected results.

In Experiments 1 and 2 it appeared that task demand was a composite of the demands associated with with each target in a target pair. As the demand associated with one target in the pair decreased, there was an increase in the availability of resources for the production of movements to the paired target. The fact that resources could be shifted between the targets was strongly evidenced by the speed-accuracy trade off functions obtained for fixed targets (i.e targets that do not increase in width, but are paired with a variety of targets of increasing widths) compared with those obtained for the variable targets (i.e. those targets which

increase in width when paired with a fixed target). For the variable targets there was a linear relationship between task difficulty, expressed in Fitts' terminology, and movement time. As target width increased, movements became faster and less accurate. For movements to the fixed targets however, as the paired target increased in width, movements to the fixed targets became faster and more accurate. The function relating speed of movement to movement difficulty for movements to the fixed targets appeared to be the inverse of the same function relating movement time and difficulty for movements to the variable targets. Apparently, resources were being divided between the targets in the target pair, and the nature of the speed-accuracy trade-off function obtained was dependent upon where those resources were being directed.

Explanations of the phenomenon described by Fitts' Law revolve around the processing of visual feedback information and the issuance of within movement corrections (Crossman and Goodeve, 1983; Keele, 1968; Howarth and Beggs, 1972; Howarth, Beggs and Bowden, 1971). While each theory differs in formulation, they all rely on visual information being used to determine the movement error and to allow for within movement correction. The importance of visual information in peforming aiming movements has been demonstrated by numerous authors (Hay, 1979; Holding, 1968; Howarth and Beggs, 1981; Kinchla and Smyzer, 1967; Lee, Lishman and Thomson, 1982; Sharp and Whiting, 1974; Thomson, 1983).

Experiment 2 investigated the relationship between availability of visual information and the subsequent speed-accuracy trade-off functions obtained in the reciprocal tapping task. If it is assumed that the correction of movement errors is dependent upon the availability of visual information, then it might be anticipated that the error associated with a movement is related to the time spent viewing the aimed for target or the limb as it moves to the target. It could also be assumed that as the size of the aimed for target increases, the uncertainty related to the position of the target decreases. Carlton (1981) demonstrated that visual information was not required in guiding the first 93% of movement, and Wallace and Newell (1983) demonstrated that the accuracy of sighted versus unsighted movements was equivalent, as long as the difficulty of the movement did not exceed 4.58 bits, representing an

accuracy in the order of 93% for blind movements. Both of these findings suggest that visual information regarding the position of the aimed for target is more important in accurate performance of an aiming response than is visual information derived from monitoring the transport of the limb to the target.

Experiment 2 demonstrated that as the size of one of the targets in a target pair increased in width, the number and duration of visual fixations on that target decreased, while the error associated with that target increased. Similarly, as the size of one target increased and fixations on that target decreased, duration of fixations on the paired target increased, while at the same time errors decreased. The demand associated with a particular target is evidenced by the frequency and duration of visual fixations on that target. Limitations in performance are the result of the subjects' inability to fixate both targets simultaneously, when the targets are outside the range of the visual field. Processing limitations become evident when the subject is required to alternate fixations between targets. As one of the targets becomes wider, producing difficulties of movement in the order of 4 bits, the neccesity to visually fixate the target in order to perform an accurate movement, is reduced. The subject is then able to devote more time fixated on the smaller target, with the result that movements can be more accurately controlled. The result is movements which can be made faster while at the same time becoming more accurate.

The results of Experiments 1 and 2 suggest that Fitts' Law is the product of specific task demands, in which the demand associated with each target in a target pair is equal. Speeding of movements in such cases results in increased error. In Experiments 1 and 2 the demand associated with one target in the target pair is reduced, with the result that performance of movements to the more demanding target improves. Combining these observations with those of Fitts (1954) suggests that two factors are important in determining the accuracy with which a speeded movement can be performed. The two factors which appear important in determining the accuracy with which a speeded movement can be performed are the overall demand associated with the targets in a target pair, which is the sum of the demands of the individual targets; and, the policy of allocating resources between

the two targets.

The importance of the policy of resource allocation was demonstrated in Experiment 5. When the subjects perceived that there was a difference in demand associated with the targets in the target pair, performance was adjusted to reflect this difference, even though there was no actual difference between the targets. The importance of this finding demonstrates that performance is dependent not only on physical task constraints imposed by manipulation of task parameters such as amplitude and movement accuracy, but also on the effect that these manipulations have on the subject's perception of the difficulty of the task. The fact that actual changes in task demand might not be perceived as such by the subject, was demonstrated in Experiment 4. Based on the assumption that subjects are limited in their ability to make categorical judgements, it was shown that changes in task difficulty with orders of magnitude less than that required to make a categorical distinction, would not be perceived as changes by the subject. Performance outcome reflected the number of categories observed by the subject, rather than the number of actual differences presented to the subject. Perception of task difficulty and its subsequent influence on performance appears to be a critical factor in determining the realtionship between speed and accuracy of movement in different movement situations.

The failure of Fitts' Law to accommodate movements produced in times less than a simple reaction time (< 250 msec), for which insufficient time is available for the necessary processing of visual feedback information, led researchers to investigate the relationship between speed and accuracy of rapid movements (< 250 msec) and to examine the mechanisms underlying their control. Such approaches were generally based on the assumption that the production of movement may be based on some form of programmed control, in which certain movement parameters could be preset some time prior to the execution of the movement. Such an approach was adopted by Schmidt et al. (1978, 1979). They pointed out that movements of fixed amplitude require larger initial impulse forces in order to be performed more rapidly. This derives from the simple fact of physics that for a body of fixed mass, velocity depends upon the forces applied to the body. The concept of the motor

program as presented by Schmidt et al. (1978) suggests that a prestructured set of motor commands can be executed to complete a movement without involving peripheral feedback information. Subsequently, if movements can be structured in advance, then errors contained in the programs or in the recruitment of motor units involved in their execution, cannot be corrected until execution of the program has been completed. The basic premise of the Schmidt et al. (1978, 1979) formulation is that the variability in the horizontal distance travelled (effective target width, W(e)) is proportional to the the within subject variability of the velocity, following acceleration. Since the velocity of the movement is proportional to the magnitude of the accelerative impulses, the variability in veleocity is consequently, proportional to the variability in impulse force and the time over which the impulse acts. Hence, the effective target width is proportional to both the variability of impulse force, and impulse duration. The Schmidt et al. formulation has, therefore, very specific predictions regarding the relationship between speed and accuracy of movement. Faster movements, requiring larger accelerative impulse forces, will be associated with larger effective target widths.

Experiments 1 and 2 demonstrated that increasing the velocity of movement does not guarantee that there will be an associated increase in movement error. Even when movement times were relatively short ($<$ 200 msec) it was possible for subjects to make faster movements, which were more accurate. These movements had higher peak velocities, presumably brought about by larger, more variable accelerative impulses; and yet were less errorful than slower movements with lesser accelerative impulses. This latter finding tends to contradict the position presented by Schmidt et al. (1978, 1979).

The important role of the motor program in the production of movement is supported by research from many areas including the neurosciences (Mott and Sherrington, 1895; Asatryan and Fel'dman, 1965; Fel'dman, 1974a, 1974b; Taub and Berman, 1968; Bizzi, Polit and Morasso, 1976; Bizzi, Dev, Morasso and Polit, 1978; Bizzi and Polit, 1979; Gallistel, 1981), the behavioral sciences (Boomer, 1965; Pew, 1966, 1974; Lenneberg, 1967; Posner and Keele, 1968; Keele, 1968, 1981; Laver, 1970; Merton, 1972; Schmidt, 1975; Raibert, 1977;

Terzuolo and Viviani (1979); Falkenberg and Newell, 1980; Kelso and Holt, 1980) and the field of artificial intelligence (Miller, Gallanter and Pribram, 1960; Fitch and Turvay, 1978; Arbib, 1981). While the motor program plays an important role in the execution of many skills, the role of feedback information cannot be overlooked (Abbs, Graco, and Cole, Unpublished paper; Skavensk, 1972; Forsberg, Grillner and Rosignol, 1977; Massion and Gahery, 1979; Miles and Evarts, 1979; Glencross (1973, 1975, 1977) noted that when rapid movements (< 200 msec) are executed, they are performed smoothly and with precision. When feedback information is blocked or distorted, the fine grading of movement and its temporal precision, are lost (Bossom, 1974; Laszlo, 1966, 1967, 1968; Glencross and Oldfield, 1975). It would appear that in order for a central control process (a motor program) to be executed efficiently, it must be integrated in some way with peripheral sensory information.

Glencross has proposed a two stage integrated model of movement control which combines both program and feedback elements (Glencross, 1977; Glencross and Oldfield, 1975; Glencross and Gould, 1979). The first stage, the executive control system, is feedback dependent and its performance is based on an analysis of movement requirements and relationship between output requirements and the produced response. The second stage consists of the motor program which, once intitiated, will run its full course without intervention. Such a model could be applied to explain the results of Experiments 1 and 2. When the demands associated with both targets are high (i.e two small targets are paired together) the subject alternates visual fixations between targets with the result that each fixation is of relatively short duration. In these high demand situations, the time devoted to evaluation of visual feedback is divided equally between the two targets. When the demand associated with one of the targets is reduced, it becomes less important for the subject to monitor feedback information since he can rely on the output of the motor program to acquire the target. This allows him to devote more time to the collection of visual feedback information from movements to the more demanding target which can be utilized in upgrading or correcting the response formulation for acquiring the more demanding target. Hence, it is possible for the subject to move faster without reduced accuracy. This approach

does not predict that increased availability of visual feedback information would result in movements for which the variability associated with the accelerative impulses was less when compared to movements of similar velocity produced with less opportunity for visual monitoring. Instead, it suggests that the greater variability associated with the faster movements can be subsequently corrected during the terminal phase of the movement. This prediction could be tested, and would offer some important information regarding the role of visual information in controling rapid aiming movements.

An important distinction has to be made between the movements examined in Experiments 1 and 2 and those employed by Schmidt et al. (1978, 1979). In the reciprocal tapping task it is possible for the subject to utilize visual feedback information on an ongoing basis for the correction of movement. That is, the success of a particular movement could be evaluated and the information acquired, used to modify upcoming movements. This is not the case for the single rapid aiming movement employed by Schmidt et al. Schmidt (1980) suggests that subjects can switch between feedback dependent and programmed modes of control depending upon available capacity and the attentional demands placed upon the subject by a particular situation. He further suggests that the subject will adopt feedback control when no other actions are present or the actions require little or no attention, since the cost of allocating attention is not a problem. The current experiments would suggest that rather than switching between feedback and programmed control, the subject will incorporate as much visual feedback information into updating performance as is available or can be collected. Limitations are seen, therefore, when visual feedback is not available (blinded movements), or the subject cannot acquire the information because he is restricted to acquire information from one source at a time. This approach would parallel the distinction made between resource limitations and data limitations as proposed by Navon and Gopher (1979). Resource limitations would be equated with the subjects ability to fixate one target in preference to the other, while data limitations would refer to the availability of feedback information.

The desire to find simple mathematical models which adequately describe the relationship between speed and accuracy of movement is evidenced by the formulations of Fitts (1954); Crossman and Goodeve, 1983; Welford ,1966; Beggs and Howarth, 1972; Howarth and Beggs, 1981, 1985); Howarth, Beggs and Bowden, 1971; Carlton, 1981; Schmidt et al., 1978, 1979; Wright and Meyer, 1983.

Formal tests of such models, which do not violate deductive logic, are difficult to formulate, especially when the 'thing' that is to be tested is not directly observeable. Unfortunately, many of the formulations regarding speed-accuracy trade-off can be easily falsified. In many cases severe constraints must be placed upon the arguments presented. Such constraints would relate to the initial conditions imposed by the experimenter, through the manipulation of task parameters, and any auxilliary assumptions that have to be made in order for the proposed realtionship to hold. For example, Wright and Meyer (1983) demonstrated that the speed-accuracy trade-off function described by Schmidt et al. (1979) holds if and only if, movements are constrained by time. Similarly, the formulation of Fitts (1954) appears to hold only for movements which are performed slowly, that is, with sufficient time for the utilization of visual feedback information.

In the current series of experiments a number of situations have been identified in which the expected relationship between speed and accuracy of movement does not appear to hold. Rather than being merely disconfirming instances of the the expected phenomenon of speed-accuracy trade-off, these observations suggest that many factors are jointly responsible for determining the speed and accuracy with which movements can be performed. Experiments 1 and 2 demonstrated that movements could be speeded without loss of accuracy. This improvement in performance appeared to depend not only on the availability of visual feedback information, but also on the availability of visual processing resources to utilize the available information. The utilization of visual feedback was evidenced by the frequency and duration of the visual fixation on the aimed for target. As the duration of the visual fixations increased, aiming errors decreased. The increase in duration of visual fixation was brought about by reducing the demand associated with one target in the target pair, thus reducing the

uncertainty regarding its position, and allowing the subject to acquire the target without the need for visually mediated correction.

Experiment 3 demonstrated that the nature of the movement constraints imposed by the experimenter can influence the speed and accuracy with which the aiming movement can be performed. Constraining the subject by movement accuracy appears to be the least demanding performance situation. Increased demand can be brought about by introducing a temporal estimationcomponent to the task, by requiring the subject to perform the required movements in prescribed movement times. In such situations the subject is required to establish a criterion for movement accuracy, and to process information regarding the temporal accuracy of the produced movement. The fact that movements of differing velocities can be performed with equivalent accuracies suggests a degree of disassociation between speed and acuracy of movement. The apparent disociation of the mechanisms underlying the final position of movement and its velocity has been supported by the findings of Bizzi and Polit (1979). They suggest that motor programs specify, through the selection of a set of length and tension parameters in agonist and antagonist muscles, an equilibrium point between the two sets of muscles that correctly positions the limb in relation to the visual target. This position has been supported by a number of researchers (Houk, 1979; Schmidt and McGown, 1980; Kelso and Holt, 1980). They qualify this position with the suggestion that this process must be accompanied by a mechanism which controls movement velocity. Bizzi et al. (1979) state that:

> "The postulated independence of the processes controlling velocity, indicates that a number of parallel processes underlie arm movement, and that motor control may be thought to be organized in a modular fashion." (p. 193)

It appears from the current experiments, that rapid movements can be terminated accurately given sufficient visual feedback information. This feedback information is apparently utilized to correct the variability associated with the accelerative impulse. As a result, it can be made to appear that speed and accuracy of movement are unrelated. The proposal that a number of parallel processes underly the production of aimed movements is

an important one. Experiment 4 highlighted the importance of workload margin in understanding speed-accuracy trade-off. Certain task manipulations, while increasing the nominal difficulty of the task in information terms, do not appear to have their anticipated effects since they are not perceived as changes by the subject. Experiment 5 demonstrated that knowledge of the physical constraints of the task is not neccessarily sufficient to predict the outcome of a movement of given difficulty since performance outcome appears to depend, in part, on the subjective evaluation of task difficulty of the subject.

In order to gain a complete understanding of the relationship between speed and accuracy of movement, it appears neccessary to evaluate task demand along a number of dimensions, with the intent of developing accurate measures of task composition. Williams (unpublished paper) has developed an approach to the acquisition of knowledge which is based on the identification of all antecedent factors which contribute to the production of a particular outcome. As well as determining the range of factors involved in the production of a particular outcome, it is also neccessary to determine the range of sufficency for each factor. That is to say, a determination of the range of values for any factor that is sufficient to produce the anticipated outcome. This notion suggests that it is not only neccessary for a particular factor to be accounted for, but also that each of these factors must be sufficient in its own way to achieve the objective. For example, while its is neccessary for vision to be available in order to process visual feedback information, it is not sufficient. There must be visual information available to process, but further, the subject must be able to direct resources to the acquisition of that information. As demonstrated in Experiment 2, processing of visual feedback information is dependent upon the subject visually fixating the aimed for target. The degree to which information can be utilized appears dependent upon the duration of the visual fixation.

The proposition of Williams (unpublished paper) would give arguments which had the following form:

IF {f1,f2,f3,....fn} THEN E

In such a case the expected outcome, E, would be dependent upon a number of factors, f1 to

fn, occurring, neccessarily, with the required sufficiency.

The method of examination of the relationship between speed and accuracy of movement suggested above bears striking resemblance to contemporary views of attention. The dual-task paradigm is commonly employed in the study of attention. In the dual-task paradigm, the nature of interference occuring when two tasks are performed simultaneously as opposed to separately is used to infer the nature of the resource compositions of the two tasks. When two tasks are attempted at the same time there is typically some associated cost. Either, there is a deficit observed in performance of either or both tasks compared to the single task performance, or there is a trade-off in performance in which performance of one task is maintained close to its single task level, at the expense of the performance of the second task. Prevalent explanations of the dual-task interference effects revolve around the belief that the two tasks draw upon resources from a common resource pool (e.g., Kahneman, 1973; Kerr, 1973; Norman and Bobrow, 1975) or a number of resource pools (e.g. Navon and Gopher, 1979; Wickens, 1980). When the demand for a limited resource pool exceeds the availability, then interference occurs between tasks which are competing for the resource.

According to Navon and Miller (1986), an obvious case of competition would arise when two tasks require incompatible use of a single sensory mechanism. For example, it is impossible to look in two different directions at the same time. In Experiments 1 and 2, there is competition between the two targets for use of vision. The result is an observed trade-off between performance on one target and its partner such that performance is improved on the target which is viewed when compared to the target which is not viewed. Competition for structural resources, such as vision, becomes one of the factors which is important in specifying the level of performance in the aiming task.

Navon and Miller (1986) report that many instances of dual-task interference cannot be attributed to competition for peripheral structures. The concept of interference has nonetheless, been extended to these instances. In these cases, processes of central interference are thought to occur when tasks compete for some limited central mechanisms (Norman and

Bobrow, 1975). While there is no evidence for the existence of such central mechanisms, they are thought to come in units which can be distributed among concurrent processes (Navon, 1984, 1985). As stated by Navon and Miller (1986):

> "In any case, the common feature of all these explanations is that they attribute task interference to the competition of tasks for the use of some scarce entities - call them resources, mechanisms, or structures."(p.1).

Norman and Bobrow (1975) present a theory of performance which is based on an interesting characteristic of the human processing system which they refer to as the 'principle of graceful degradation' (p. 45). This characteristic implies that when the limited capacity processing system is overloaded, there appears a smooth degredation in performance rather than a calamitous failure. A process will produce output therefore, according to the data input to the process and the resources allocated to it. Norman and Bobrow (1975) acknowledge that resources are not all of one kind. As a result they suggest that:

> "A full analysis of interprocess competition requires examination of each resource composition separately, including analysis of the trade-offs among various resources and the criteria for scheduling resources." (p. 45).

This is equivalent to saying that knowledge of the full range of factors influencing performance and their associated sufficiencies is necessary in order to predict performance outcome.

Norman and Bobrow also introduce the concepts of resource and data limitations. Whenever an increase in the amount of resources devoted to a task results in increased performance then the task (or performance on the task) can be considered to be resource limited. In Experiments 1 and 2 performance increased as the frequency and duration of visual fixation increased, indicating that performance was resource limited. Whenever a task is independent of processing resources, the task is considered to be data limited. For example, in Experiment 4, decreasing demand on the subject by increasing the width of the aimed for targets did not necessarily result in increased performance since the subject was unaware of the change in demand. In this case the subject could be thought to be data limited. In viewing

the competition for limited resources by several active processes, Norman and Bobrow suggest that the performance resource functions of the processes are critical in determining the effects observed. Obviously, no interference effects will be observed when the demand for resources of the competing processes does not exceed the total available resources. Interference will only occur when a process is operating in its resource limited region. It is possible that one of the competing processes may be data limited while the other is resource limited with the result that interference effects are not symmetrical. In Experiments 1 and 2 increasing the width of a target beyond 4 cm had no effect on the error associated with that target. It did, however, have an effect on the paired target. Increasing the width of a target beyond 4 cm still led to improved performance on the smaller paired targets. According to Norman and Bobrow (1975) the observed symmetry or assymmetry of interference between tasks is dependent upon task instructions and the subject's strategy, which determines which of the tasks receives highest priority. This latter point appears to be supported by the data concerning visual fixations obtained in Experiment 2.

Norman and Bobrow (1975) suggested that there may be a variety of resource types, a contention supported by extensive research findings (Brooks, 1968; Allport, Antonis and Reynolds, 1972; North, 1979). According to Navon and Gopher (1979):

> "Not only can the processing system as a whole be involved in several activities in variable proportions but a specific mechanism or modality is not necessarily dominated by one process exclusively but instead can accommodate more than one process at the expense of quality or speed of performance. In other words, resources may not be homogenous because the human system is probably not a single channel mechanism but rather a complicated system with many units, channels and facilities. Each may have its own capacity (which is, roughly, the limit or amount of information that can be stored, transmitted, or processed by the channel at a unit of time)." (p. 233).

According to this view performance depends on the amount of each resource required to perform the task and the demands placed upon them. Navon and Gopher refer to this as the

'demand function'. The processing system appears capable of being involved in several activities in variable proportions. Furthermore, specific mechanisms or modalities are not necessarily dominated by one process exclusively, but can handle several at the expense of time or quality. In brief, a number of different types of performance function may be observed. In the fixed proportions function the requirements for specific resources must be met rigidly. For example, if A and B refer to different resource types, then the fixed proportions function would propose that an increase in availability of type A resources without a concommitant increase in type B resources will not improve performance. In the variable proportions case an optimal combination of resources is defined. Variations from this optimal combination can be tolerated however, and hence peformance usually benefits from an increase in any useable resource. In many cases certain resources are irrelevant for the performance of the task and an increased availability of them will not result in changed performance. According to Navon and Gopher the nature of a task can be defined as the relative weights of the various resources in the demand composition. The difficulty of a task will change that task qualitatively if it modifies the relative weights of resources. Only when the relative weights remain constant, i.e. increase proportionally, does a task remain the same.

This last point is important in viewing the results of Experiments 1 and 2. In these experiments it can be argued that the relative weights of resources do not remain constant and that this change in the relative weights is responsible for the observed changes in performance. In both the Fitts' task where equal sized targets are paired, and the Schmidt et al. tasks where single aiming movements are performed, relative weightings are unchanged throughout the experiments. The speed-accuracy trade-off functions obtained are therefore, special cases in which the realtive weights of resources remain constant throughout the task.

In Experiment 3 it was demonstrated that various task constraints have different effects on task performance. That is, performance in target constrained tasks was significantly better than in time constrained tasks, which was better than performance in metronome paced tasks. The multiple resource approach would suggest that these tasks differed in their resource compositions with the resulting performance differences. Navon and Miller (1986) also

propose that tasks may interfer because the output, or side-effects of one task are harmful to the processing of the other. Navon (1985) refers to this as 'outcome conflict'. In Experiment 3, the effects of such outcome conflicts were evident in the performance of time constrained and paced movements. In time constrained movements subjects are required to make temporal estimations while at the same time producing movement with a temporal component. In paced movements, subjects were required to monitor an auditory signal which provided information regarding the temporal demands of the task. The outcomes of these estimation tasks and monitoring tasks appears to interfer with the temporal organization of the output movement.

The importance of resource composition in determining the level of performance of the output movement may be crucial. The speed with which a movement is produced and the error associated with that production is dependent upon the integration of many factors. These factors include modality effects, such as the demand placed upon vision, and the structural limitations of the motor system to produce rapid movements; perceptual effects, such as the subject's ability to make categorical distinctions; factors involving the resource composition of the task, which are influenced by the manner in which the task is constrained; policies of resource allocation adopted by the subject, which can be influenced by both physical changes in task demand brought about by changes in required accuracy or speed, or by perceptual factors such as in the case of perceptual illusion. A clearer understanding of the realtionship between speed and accuracy of movement may only be obtained when the complete range of factors influencing performance are identified and the manner in which these factors interact is determined. The current experiments present some evidence to suggest that a number of factors interact to determine performance outcome. It remains to quantify the effects that each factor has and to determine the exact nature of the interaction between factors.

8. REFERENCES

Abbs, J. H., Gracco, V. L. and Cole, K.J. Control of multi-movement coordinations: Sensorimotor mechanisms in speed motor programming. Unpublished paper. Speed motor control laboratories, Weisman Centre on Human Development, University of Wisconsin - Madison.

Adams J. A. (1976) Issues for a closed loop theory of motor learning. In G. E. Stelmach (Ed.) *Motor Control: Issues and Trends.* New York: Academic Press.

Annett, J., Golby, C. W., and Kay, A. (1958) The measurements of elements in an assembly task - the information output of the human motor system. *Quaterly Journal of Experimental Psychology, 10,* 1-11.

Arbib, M. A. (1981) Perceptual structures and distributed motor control. In J. M. Brookhart and V. B. Mountcastle, (Eds.) *Handbook of Physiology, Section 1: The nervous system. Vol. 11.* American Physiological Society, Bethesda: Maryland.

Asatryan, D. G., and Fel'dman, A. G. (1965) Biophysics of complex systems and mathematical models. Functional tuning of the nervous system with the control of movement or maintenance of a steady posture. 1. Mechanographic analysis of the work of the joint on execution of a postural task. *Biophysics U.S.S.R., 10* , 925-935.

Bailey, G. B., and Presgrave, R. (1958) *Basic motion timestudy.* New York: McGraw Hill.

Beggs, W. D. A. and Howarth, C. I. (1972) The accuaracy of aiming at a target: some further evidence for a theory of intermittent control. *Acta Psychologicaa, 36,* 171-177.

Bizzi, E., Polit, A., and Morasso, P. (1976) Mechanisms underlying the achievement of final head position. *Journal of Neurophysiology, 39,* 435-444.

Bizzi, E., Dev, P., Morasso, P. and Polit, A.(1978) Effect of load disturbances during centrally initiated movements. *Journal of Neurophysiology, 41,* 542-556.

Bizzi, E., and Polit, A. (1979) Characteristics of motor programs underlying arm movements in monkeys. *Journal of Neurophysiology, 52,* 183-194.

Bossom, J. (1974) Movement without proprioception. *Brain Research, 71,* 285-296.

Brooks, V. B. (1974) Some examples of programmed limb movements. *Brain Research,71,* 299-308.

Carlton, L. G. (1981) Processing visual feedback information for movement control. *Journal of Experimental Psychology, 7, 5,* 1019-1030.

Coombes, C. H., Dawes, R. M., and Tversky, A. (1970) *Mathematical Psychology.* Englewood Cliffs, New Jersey: Prentice Hall.

Cooke, J. D., and Eastman, M. J. (1977) Long loop reflexes in the tranquilized monkey. *Experimental Brain Research, 27,* 491-500.

Cremieux, J. and Amblard, B. (1978) Effects of visual movement deprivation on a visuo-motor task in cat. *Neuroscience Letters, Supp.1,* 387.

Crossman, E. R. F. W. (1953) Entropy and choice time: the effect of frequency imbalance on choice responses. *Quaterly Journal of Experimental Psychology, 5,* 41-51.

Crossman, E. R. F. W., and Goodeve, P. J. (1983) Feedback control of hand movement and Fitts' Law. Paper presented at the meeting of the Experimental Psychology Society, Oxford, 1963. *Quarterly Journal of Experimental Psychology, 35A,* 257-278.

Falkenberg, L. E. and Newell, K. M. (1980) Relative contributions of movement time, amplitude and velocity to response initiation. *Journal of Experimental Psychology: Human Perception and Performance, 6, 4,* 760-768.

Fel'dman, A. D. (1974) Control of muscle length. *Biofizica, 19,* 749-753.

Fel'dman, A. D. (1974) Change of muscle length due to the shift of the muscle load system. *Biofizica, 19,* 534-538.

Fitts, P. M. (1954) The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47,6,* 381-391.

Fitts, P. M., and Peterson, J. R. (1964) Information capacity of discrete motor responses. *Journal of Experimental Psychology, 67,* 103-112.

Fitts, P. M., and Radford, B. K. (1966) Information capacity of discrete motor responses under different cognitive sets. *Journal of Experimental Psychology, 71,* 475-482.

Forssberg, H., Grillner, S., and Rossignol, S.(1977) Phasic gain control of reflexes from the division of the pair during spinal locomotion. *Brain Research, 132,* 121-139.

Friedman, A., and Polson, M. C. (1981) Hemispheres as independent resource systems: Limited capacity processing and cerebral specialization. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 5, 1031-1058.

Fullerton, G. S., and Cattell, J. McK. (1892) On the perception of small differences. *University of Pennsylvania Philosophical Series,* No. 2.

Galiistel, C. R. (1980) *The organization of action: A new synthesis.* Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Glencross, D. J. (1973) Response complexity and the latency of different movement patterns. *Journal of Motor Behavior, 5,* 95-104.

Glencross, D. J. (1975) The effects of changes in task conditions on the temporal organization of a repetitive speed skill. *Ergonomics, 18,* 17-28.

Glencross, D. J. (1977) Control of skilled movements. *Psychological Bulletin, 84,* 14-29.

Glencross, D. J., and Oldfield (1975) The use of ischemic nerve block procedures in the investigation of the sensory control of movements. *Biological Psychology, 2,* 165-174.

Glencross, D. J., and Gould, J. H. (1979) The planning of precision movements. *Journal of Motor Behavior, 11,1,* 1-9.

Hancock, P. A., and Newell, K. M. (1985) The movement speed-accuracy relationship in space-time. In H. Heuer, U. Kleinbeck, and K. H. Schmidt (eds.) *Motor behavior: programming, control and acquisition.* New York: Springer-Verlag.

Hay, L. (1978) Accuracy of children on an open-loop pointing task. *Perception and Motor Skills, 47,* 1079-1082.

Hay, L. (1981) The effect of amplitude and accuracy requirements on movement time in children. *Journal of Motor Behavior, 13,* 177-186.

Hick, W. E. (1952) On the rate of gain of information. *Quaterly Journal of Experimental*

Psychology, 4, 11-26.

Holding, D. H. (1968) Accuracy of delayed aiming responses. *Psychonomic Science, 12(4),* 125-126.

Houck, J. C. (1979) Regulation of stiffness by skeletomotor reflexes. *Annual Review of Physiology, 41,* 99-114.

Howarth, C. I. (1978) Startegies in the control of movement. In G. Underwood (Ed.) *Strategies of information processing.* London: Academic.

Howarth, C. I., Beggs, W. D. A., and Bowden, J. M. (1971) The realationship between speed and accuracy of movement at a target. *Acta psychologica, 35,* 207-218.

Howarth, C. I., and Beggs, W. D. A. (1981) Discrete movements. In D. M. Holding (Ed.) *Human Skills* New York: Wiley.

Howarth, C. I., and Beggs, W. D. A. (1985) The control of simple movements by multisensory information. In H. Heuer, U. Kleinbeck, and K.-H. Schmidt (eds.) *Motor behavior: programming, control and acquisition.* New York: Springer-Verlag.

Kahneman, D. (1973) *Attention and Effort* New Jersey: Prentice Hall

Keele, S. W. (1968) Movement control in skilled motor performance. *Psychological Bulletin, 70,* 387-405.

Keele, S. W. (1981) Behavioral analysis of movement. In V. B. Brooks (Ed.) *Handbook of Physiology, Section 1: The Nervous System.* The American Physiological Society, Bethesda: Maryland.

Keele, S. W. , and Posner, M. (1968) Processing of visual feedback in movement. *Journal of Experimental Psychology, 77,* 155-158.

Kelso, J. A. S., and Holt, K. G. (1980) Evidence for a mass-spring model of human neuromuscular control. In C. H. Nadeau et al. (Eds.) *Psychology of Motor Behavior and Sport.* Illinois: Human Kinetics.

Kerr, R. (1973) Movement time in an underwater environment. *Journal of Motor Behavior, 5,* 175-178.

Kinchla, R. A., and Smyzer, F. (1967) A diffusion model of perceptual memory. *Perception*

and Psychophysics, 2, 219-229.

Klapp, S. T. (1975) Feedback versus motor programming in the control of aimed movements. *Journal of Experimental Psychology: Human Perception and Performance, 2,* 147-153.

Knight, A. A., and Dagnall, P. R. (1967) Precision in movements. *Ergonomics, 10,* 321-330.

Knowles, W. B. (1963) Operator loading tasks. *Human Factors, 5,* 151-161.

Kvalseth, T. O. (1979) Note on information capacity of discrete motor responses. *Perceptual and Motor Skills, 49,* 291-296.

Kvalseth, T. O. (1979) A decision theoretic model of the sampling behavior of the human process monitor: Experimental evaluation. *Human Factors, 21,* 671-686.

Kvalseth, T. O. (1980) An alternative to Fitts' Law. *Bulletin of The Psychonomic Society, 16,* 371-373.

Kvalseth, T. O. (1981) Information capacity of two-dimensional human motor responses. *Ergonnomics, 24, 7,* 573-575.

Langolf, E. D., Chaffin, D. B., and Foulke, J. A. (1976) An investigation of Fitts' Law using a wide range of movement amplitudes. *Journal of Motor Behavior, 8, 2,* 113-128.

Laszlo, J. I. (1966) The performance of a simple motor task with kinesthetic sense loss. *Quaterly Journal of Experimental Psychology, 18,* 1-8.

Laszlo, J. I. (1967) Kinesthetic and exteroceptive information in the performance of motor skills. *Physiology and Behavior, 2,* 358-365.

Laszlo, J. I. (1968) The role of visual and kinesthetic cues in learning a novel skill. *Australian Journal of Psychology, 20,* 191-196.

Laver, J. D. M. (1970) The production of speech. In J. Lyons (Ed.) *New Horizons in Linguistics.* Harmondsworth, Middlesex, England: Penguin.

Lee, D. N., Lishman, J. R., and Thomson, J. A. (1982) Regulation of gait in long jumping. *Journal of Experimental Psychology, 8,* 448-459.

Lennerberg, E. G. (1967) *Biological Foundations of Language.* New York: Wiley.

MacKenzie, C. L. (1985) Structural constraints on timing in human finger movements. In. Goodman, D., Wilberg, R. B., and Franks, I. M. (eds.) *Differing perspectives in motor learning, memory and control.* Advances in Psychology, volume 27. Amsterdam: North-Holland.

Marteniuk, R. G., and McKenzie, C. L. (1980) A preliminary theory of two-handed coordinated control. In G. E. Stelmach and J. Requin (Eds.) *Tutorials in Motor Behavior.* Amsterdam: Elsevier-North Holland.

Massion, J., and Gahery, Y. (1979) Diagonal stance in quadruped: a postural supportfor movement. In R. Granit and O. Pampeiano (Eds.) *Progress in Brain Research. Reflex Control of Postrue and Movement.* Amsterdam: Elsevier.

Merton, P. A. (1972) How we control the contraction of our muscles. *Scientific American, 226,* 30-37.

Meyer, D. E., Smith, J. E. K., and Wright, C. E. (1982) Models for the speed and accuracy of aimed movements. *Psychological Review, 89, 5,* 449-482.

Miller, G. A. (1956) The magical number seven plus or minus two: Some limits on our capacity for processing information. *Psychological Review, 63,* 81-97.

Moray, N. (1967) Where is attention limited? A survey and a model. *Acta Psychologica, 27,* 84-92.

Moray, N. (1981) The role of attention in the detection of errors and the diagnosis of failures in man-machine systems. In J. Rasmussen and W. B. Rouse (Eds.) *Human detection and diagnosis of system failures.* New York: Plenum.

Moray, N. (1984) Attention to dynamic visual displays in man-machine systems. In R. Parasuraman and D. R. Davies (Eds.) *Varieties of attention* Orlando, Florida: Academic Press Inc.

Mott, F. W. and Sherrington, C. S. (1895) Experiments of the influence of sensory neves upon movement and nutrition of limbs. *Proceedings of The Royal Society, 57,* 480-488.

Navon, D. (1985) Attention division or attention sharing. In M. I. Posner and O. S. M.

Marin (eds.) *Attention and performance, vol. 11.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Navon, D., and Gopher, D. (1979) On the economy of the human processing system. *Psychological Review, 86, 3,* 214-255.

Navon, D., and Miller, J. (1986) The role of outcome conflict in dual-task interference. *ICS Report 8601.* University of California, San Diego; La Jolla.

Norman, D. A., and Bobrow, D. J. (1975) On data limited and resource limited processes. *Cognitive Psychology, 7,* 44-64.

North, R. A. (1977) *Task components and demands as factors in dual task performance.* (Report No. ARL-77-2/AFOSE-77-2). Urbana, ILL.: University of Illinois at Urbana - Champaign, Aviation Research Laboratory.

Paillard, J. (1979) The contribution of peripheral and central vision to visually guided reaching. In D. J. Ingle, D. J. W. Mansfield, and M. A. Goodale (eds.) *Advances in the analysis of visual behavior.* Cambridge: M. I. T. Press.

Paillard, J. (1980) The multichanneling of visual cues and the organization of a visually guided response. In G. E. Stelmach and J. Requin (Eds.) *Tutorials in Motor Behavior.* Amsterdam: North-Holland.

Pew, R. W.(1966) Acuisition of hierarchical control over the temporal organization of a skill. *Journal of Experimental Psychology, 71,* 764-771.

Pew, R. W. (1974) Human parceptual motor performance. In B. H. Kantowitz (Ed.) *Human Information Processing: titorials in Performance and Cognition.* New York: Erlbaum.

Polit, A., and Bizzi, E. (1979) Characteristics of motor programs underlying arm movements in monkeys. *Journal of Neurophysilogy, 42,* 183-194.

Posner, M. I. and Keele, S. W. (1968) On the genesis of abstract ideas. *Journal of Experimental Psychology, 77,* 353-363.

Raibert, M. H. (1977) *Motor Control and Learning by the state-soace model.* Technical report, Artificial Intelligence Laboratory, MIT.

Rolfe, J. M. (1971) The secondary task as a measure of mental load. In W. T. Singleton, J.

G. Fox, and D. Whitfield (Eds.) *Measurement of man at work.* London: Taylor and Francis.

Schmidt, R. A. (1975) A schema theory of discrete motor skill learning. *Psychological Review, 82,* 225-260.

Schmidt, R. A. (1980) On the theoretical status of time in motor program representation. In G. E. Stelmach and J. Requin (Eds.) *Tutorials in Motor Behavior.* Mew York: North Holland.

Schmidt, R. A., Zelaznick, H. N., Frank, J. S. (1978) Sources of inaccuracy in rapid movements. In G. E. Stelmach (Ed.) *Inormation Processing in Motor Learning and Control.* New York: Academic Press.

Schmidt, R. A., Zelaznick, H. N., Hawkins, B., Frank, J. S., and Quinn, J. T. (JR.) (1979) Motor output variability; a theory for the accuracy of rapid acts. *Psychological Review, 96,* 415-451.

Schmidt, R. A. and McGown, C. (1980) Terminal accuracy of unexpectedly loaded rapid movements: evidence for a mass-spring mechanism in programming. *Journal of Motor Behavior, 12,* 148-161.

Sharp, R. H. and Whiting, H. T. A. (1974) Exposure and occluded duration effects in a ball-catching skill. *Journal of Motor Behavior, 6,* 139-147.

Sheridan, T. B. (1970) On how often the supervisor should sample. *IEEE Transactions on Systems Science and Cybernetics, SSC-6,* 140-145.

Skavenski, A. A. (1972) Inflow as a source of extra-retinal eye position information. *Vision Research, 12,* 221-229.

Smith, K. U. (1962) *Delayed sensory feedback and behavior.* Philadelphia: Saunders.

Stein, R. B. (1982) What muscle variables does the central nervous system control? *The Behavioral and Brain Sciences, 5, 4,* 535-577.

Taub, E., and Berman, A. J. (1968) Movement and learning in the absence of sensory feedback. In S. J. Freedman (Ed.) *The Neuropsychology of Spatially Oriented Behavior.* Homewood, Illinois: Dorsey Press.

Taylor, M. M., Lindsay, P. M., and Forbes, S. M. (1967) Quantification of shared capacity processing in auditory and visual discrimination. *Acta Psychologica, 27*, 223-229.

Terzuolo, M. T., and Viviani, P. (1979) The central representation of learned motor patterns. In R. E. Talbott and D. E. Humphreys (Eds.) Posture and Movement. New York: Raven Press.

Thomson, J. A. (1983) Is continuous visual monitoring necessary in visually guided locomotion? *Journal of Experimental Psychology: Human Perception and Performance, 9(3)*, 427-443.

Travarthen, C. B. (1968) Two mechanisms of vision in primates. *Psychol. Forsch.* 299-337.

Wallace, S. A., and Newell, K. M. (1983) Visual control of discrete aiming movements. *Quaterly Journal of Experimental Psychology, 35A*, 311-321.

Welford, A. T. (1952) The psychological refractory period and the timing of high speed performance - a review and a theory. *British Journal of Psychology, 43*, 2-19.

Welford, A. T. (1960) The measurement of sensory-motor performance: survey and reappraisal of twelve years progress. *Ergonomics, 3*, 189-229.

Welford, A. T. (1974) On the sequencing of action. *Brain Research, 71*, 381-392.

Wickens, C. D. (1980) The structure of attentional resources. In R. S. Nickerson (Ed.) *Attention and Performance VIII.* Hillsdale, New Jersey: Lawrence, Erlbaum and Associates.

Wickens, C. D. (1984) Processing resources in attention. In R. S. Parasuraman and D. R. Davies (Eds.) *Varieties of Attention.* New York: Academic Press.

Wierwille, W. W., and Williges, R. C., and Schiflett, S. G. (1979) Aircrew workload assessment techniques. In B. O. Hartman and R. E. McKenziee (Eds.) *Survey of methods to assess workload.* London: Hartford House.

Wierwille, W. W., and Williges, B. H. (1980) *An annotated bibliography on operator mental workload assessment.* Patuxtent River, Md.: (Report SY-27R-80). Naval Air Test Center.

Williams, T. (1983) *Sociology and scientific explanation.* Unpublished paper. University of

Alberta. Edmonton, Alberta.

Woodworth, R. S. (1899) The accuracy of voluntary movement. *Psychological Monographs, 3,* #2.

Wright, C. E., and Meyer, D. E. (1983) Conditions for a linear speed-accuracy trade off in aimed movements. *Quarterly Journal of Experimental Psychology, 35A,* 279-296.

Zelaznick, H. N., Shapiro, D. C. and McClosky (1981) Effects of a secondary task on the accuracy of single aiming movements. *Journal of Experimental Psychology: Human Perception and Performance, 7(5),* 1007-1018.

Zelaznik, H. N., Schmidt, R. A., and Gielen, S. C. A. M. (1986) Kinematic properties of rapid aimed hand movements. *Journal of Motor Behavior, 18, 4,* 353-372.